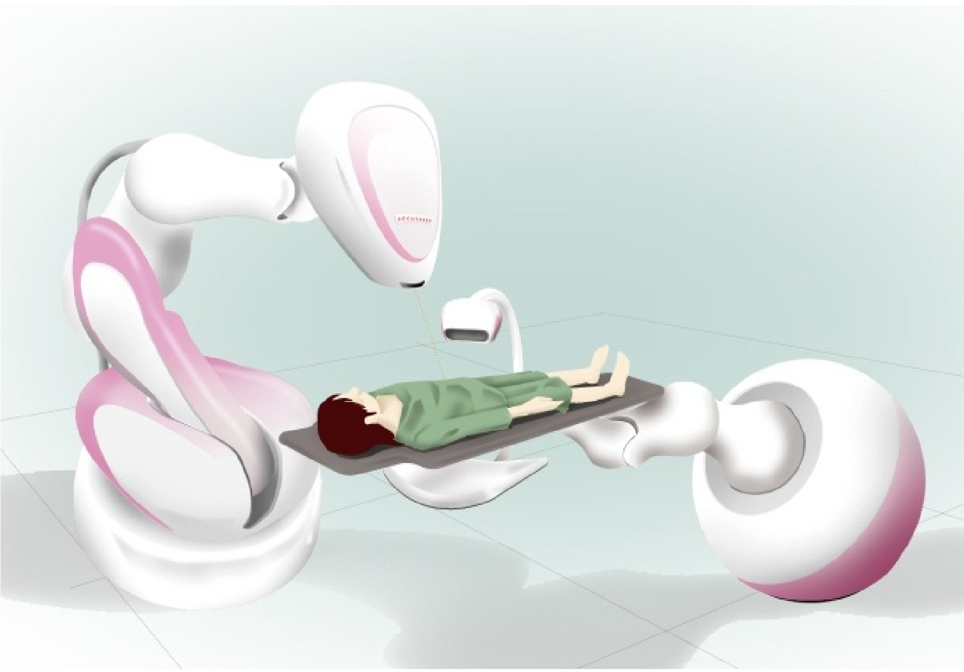
Innovation and Future of Compact Accelerator Technologies in Medicine and Industry



IPAC 2015

May, 7, 2015

Eiji Tanabe, Ph.D.

AET Inc.

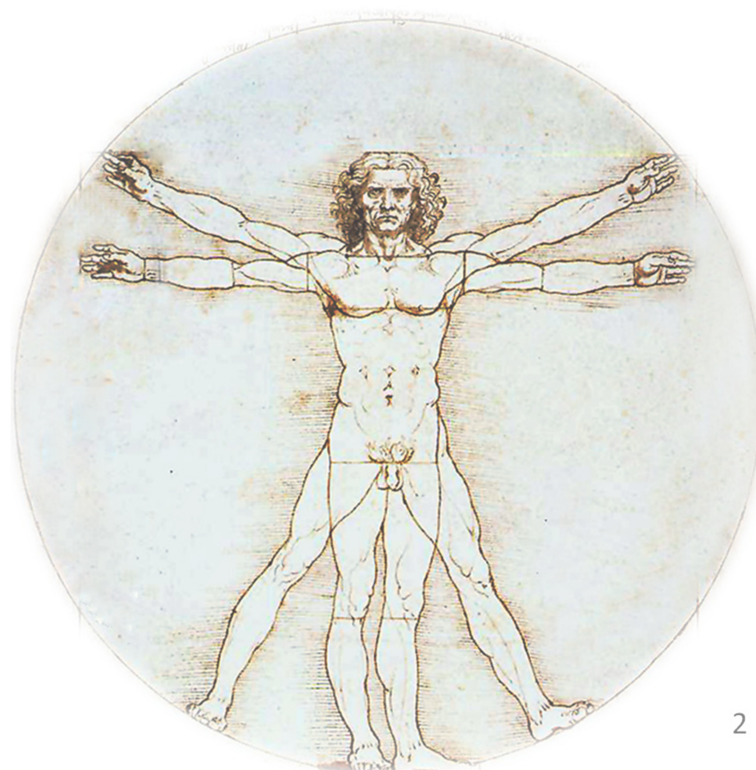
Accuthera Inc.

Univ. of Tokyo

AET

ACCUTHERA

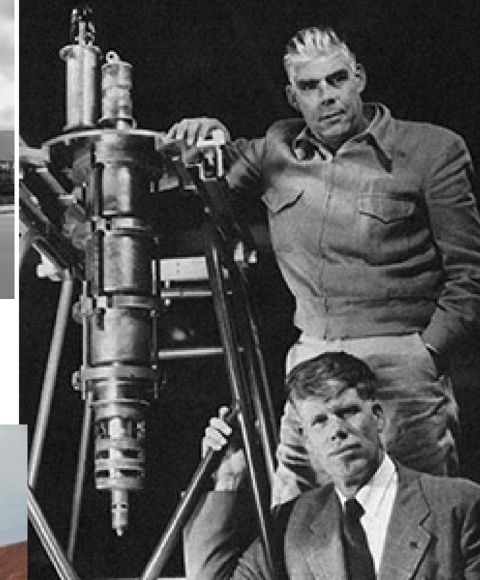
1. Introduction
2. Compact Accelerators and Technologies
3. Present and Future of Medical Accelerators
4. Other Applications of Electron Accelerators
5. Innovation and Business Development
6. Conclusion



Microwave Technology

Duke Univ. (~1975)

Varian Associates, Inc.



Varian Brothers

Stanford Univ.

Hyperthermia Research

Dr. C.J. Karzmark

Dr. M. Bagshaw

Dr. Ed Ginzton

Microwave Electron Linear Accelerators

Manager, Microwave Research
Varian, 1978

Stanford Linear Accelerator Center

Dr. Greg Loew

Dr. Thomas Weiland

Dr. William Herrmannsfeldt

Dr. Perry Wilson

Dr. Juwen Wang. Dr. Roger Miller

Start Venture!

Start venture in the garage
Sunnyvale, CA 1985

AET , Inc.
Kawasaki 1988

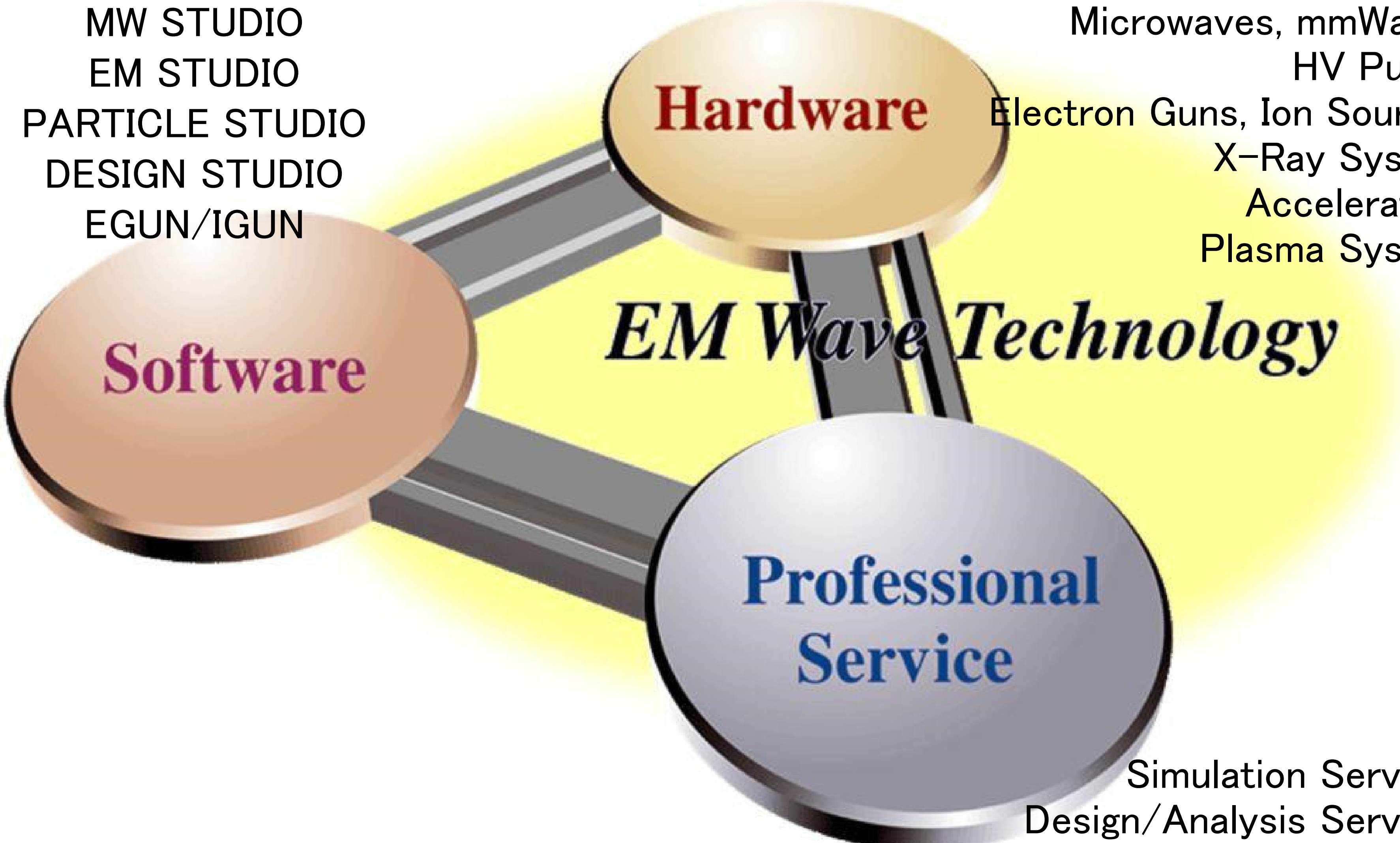
AET Associates, Inc.
Cupertino, CA 1986

AET Inc. Micon City, Kawasaki ,Japan

Advanced Electronics Technology

MW STUDIO
EM STUDIO
PARTICLE STUDIO
DESIGN STUDIO
EGUN/IGUN

Microwaves, mmWaves
HV Pulser
Electron Guns, Ion Sources
X-Ray System
Accelerators
Plasma System



Simulation Service
Design/Analysis Service
Dielectric Measurement Service
Education, Training

Questions ??????

How Many Linear Accelerators for Radiation Therapy in the World?

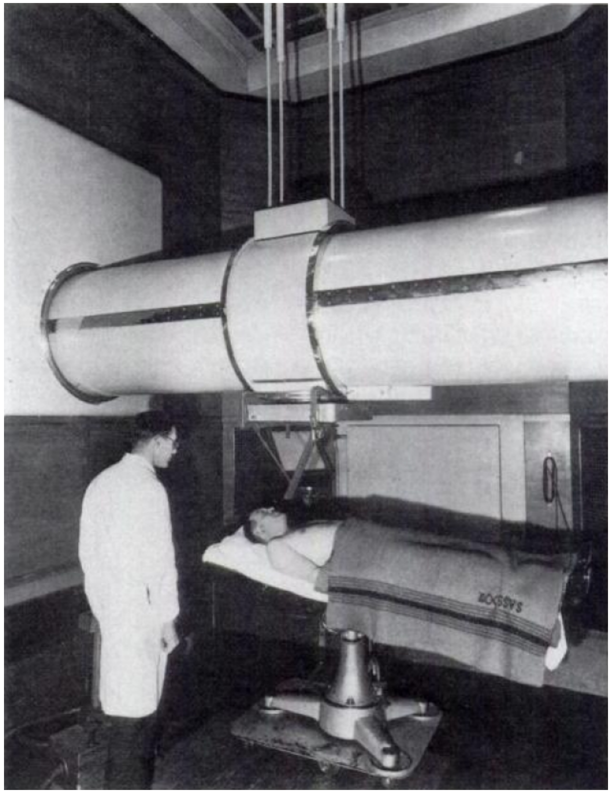
How Many Cancer Patients are Treated Daily by Linear Accelerators in the World?

When Radiation Treatment Started?

History of Medical Accelerators

1895	W.K. Roentgen, X-ray was discovered.
1913	W.D. Coolidge, Vacuum X-ray tube was developed.
1931	E.O. Lawrence, Cyclotron was developed.
1939	Medical Cyclotron Operation started. (Crocker, USA)
1940	**1.25MV pressurized type Van De Graff Accelerator was installed at Massachusetts General Hospital.**
1949	Medical treatment by 20MV X-ray of betatron. (Illinois University, Urbana, USA)
1952	The first Co-ray was installed in Oakridge.
1952	8MeV Medical Linear Accelerator Ver.1 was installed in Hammersmith Hospital. (London, UK)
1956	4MV beam generated for the first time by 6MeV Linear Accelerator in USA. (Stanford, USA)
1957	The Proton beam was used medical for the first time. (Sweden)
1962	Isocentric Microwave Linear Accelerator was installed. (USA)
1976	The first medical treatment by the Pion beam in LAMPF. (USA)
1982	The first Isocentric Cyclotron. (USA)
1990	The first Hospital use the Proton synchrotron for radiation therapy. (Romalinda, USA)
1991	Neutron radiation therapy by Super-conducting Cyclotron. (Harper, USA)

Medical Accelerators

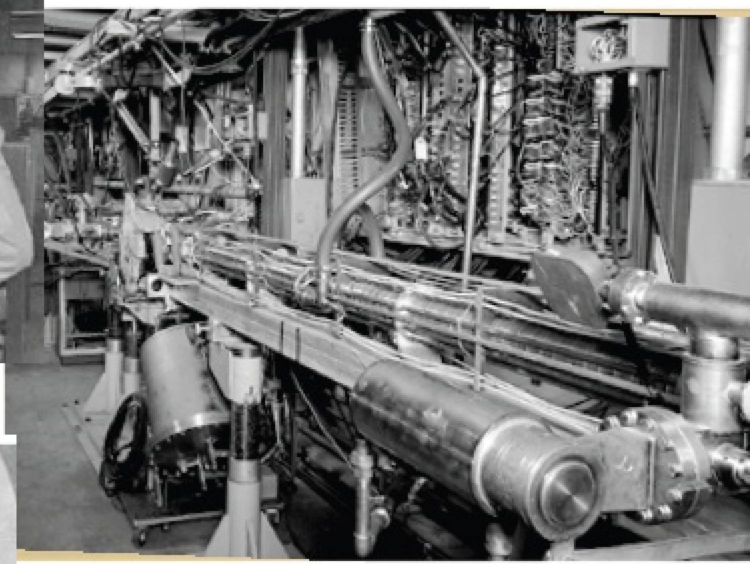


1937
1 MeV Cockcroft
Metropolitan Vickers
London

1956
First Patient, Stanford Univ.

Stanford Hansen Experimental Physics Lab (HEPL)

1939 Klystron R&D
Varian Brothers and
Prof. Hansen

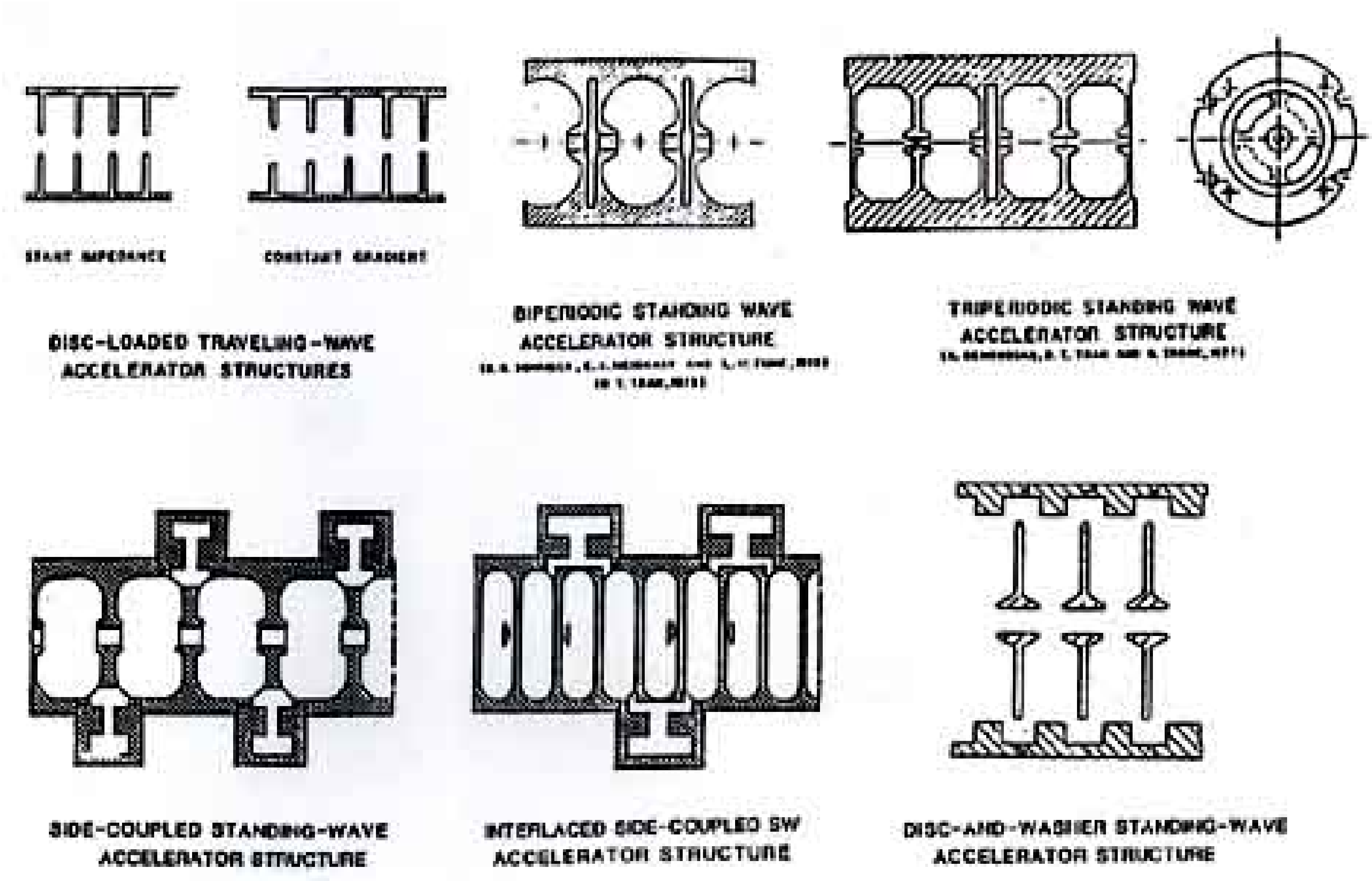


MARK Ⅳ

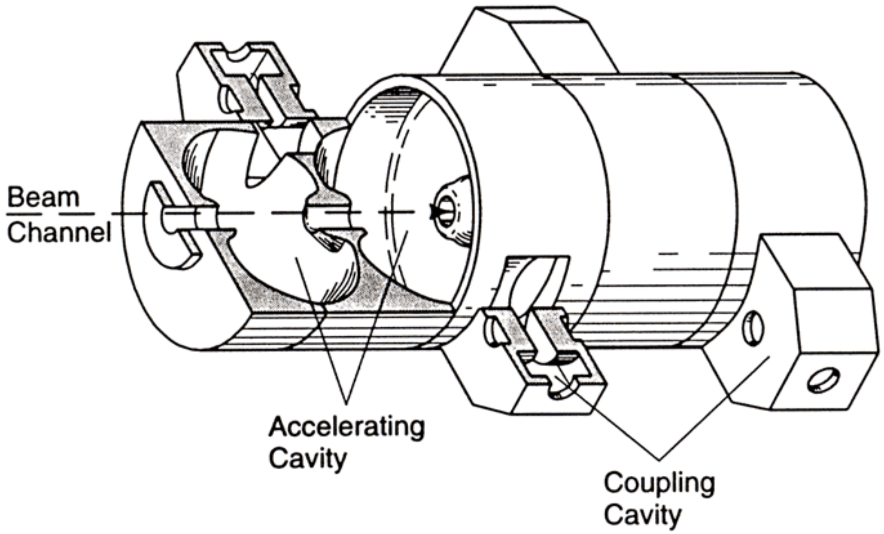
1946
MARK Ⅰ Accelerator

World First Isocentric Linear Accelerator
1962 Stanford Hospital

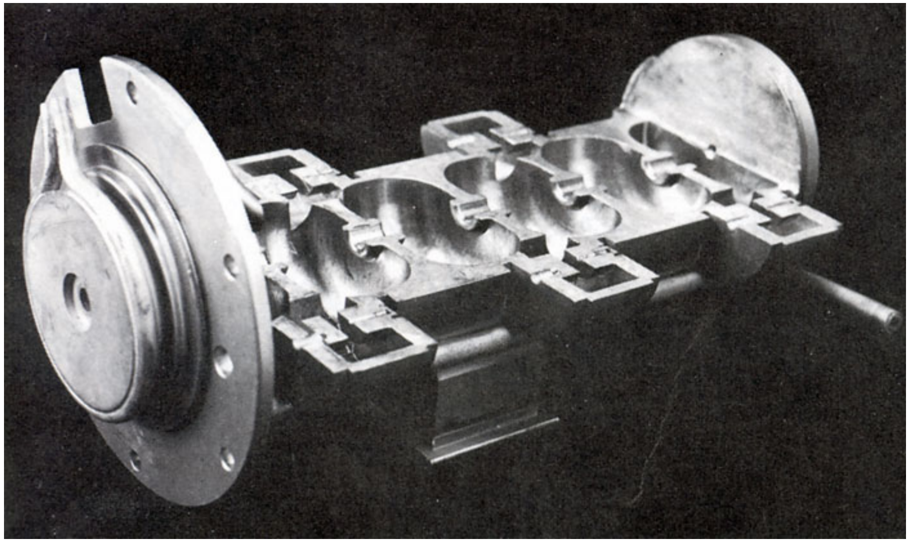
Various Microwave Linear Accelerators



Side Coupled Standing Wave Structures

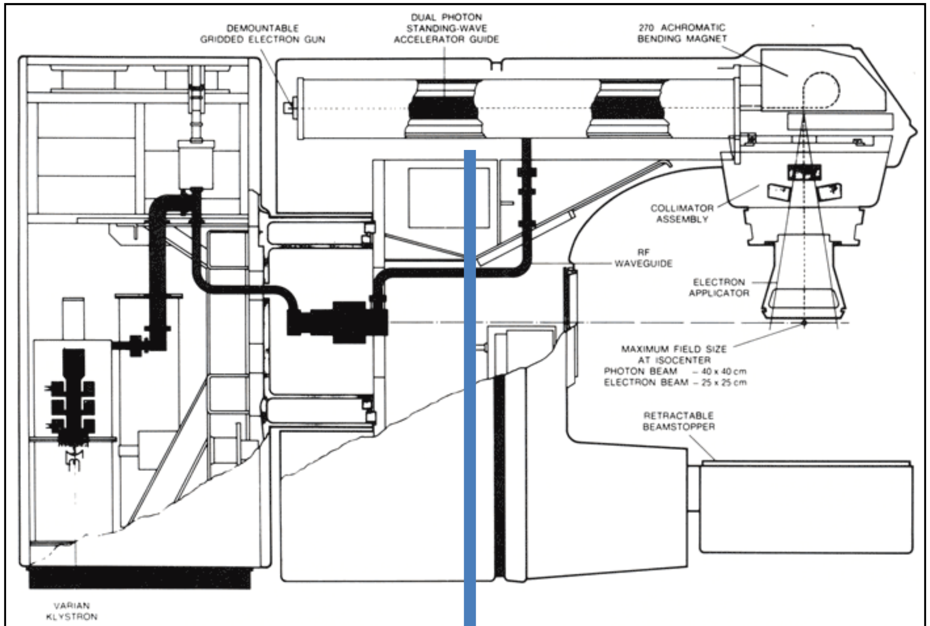


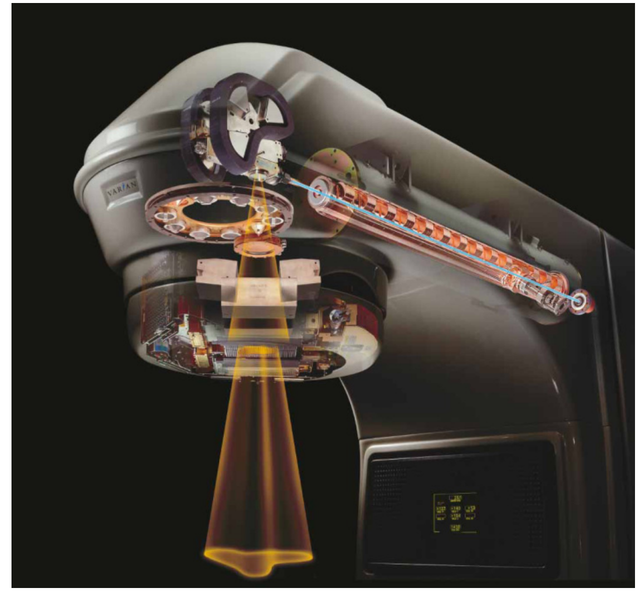
Side Coupled Standing Wave Accelerator



Varian Clinac 4 (4MeV)

Medical Electron Linear Accelerators

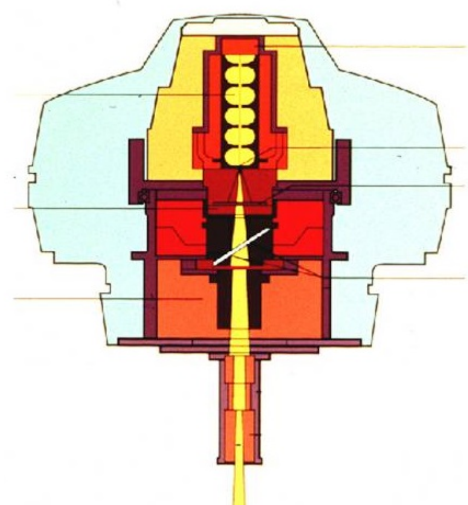




X Ray Head

Accelerator Length: 1.3m

1. Shorter and Smaller Size
2. Energy Variable(Low to High)
3. Higher Shunt Impedance



High Gradient Accelerator Structure

VOLTAGE BREAKDOWN IN S-BAND LINEAR ACCELERATOR CAVITIES

Eiji Tanabe

Radiation Division, Varian Associates Inc.
Palo Alto, California 94303

ABSTRACT

Voltage breakdown is one of the major limiting factors in the design of a high accelerating gradient linear accelerator structure. A multiple-use cavity test system was developed to establish the criteria for voltage breakdown in S-band pulsed electron linear accelerator cavities, in terms of cavity geometry, accelerating gradient, RF pulse shape and repetition rate, surface finish, temperature and external magnetic field. The experimental set-up and test procedure, as well as the experimental results, are presented.

INTRODUCTION

In the past several decades, new accelerator developments have lead to an increase in accelerator beam energy by a factor of 10 in every six years. Although accelerator technology has been steadily progressing every year, it appears that we are reaching the limit of maximum energy level due to the limited availability of funding and space, as well as technical problems. As a result, new types of accelerators with higher efficiencies (lower cost) and higher gradients (less space) become interesting. Similarly, the medical and industrial linear accelerator world is seeking more efficient and more compact structures for their new applications.

One of the major technical problems in the

shunt impedance as high as 130 MΩ/m can be acheived at S-band frequencies. However, as the shunt impedance increases, the peak electric field at the surface, especially at the nose, also increases. Using the LALA program, various cavity geometries were studied in terms of peak surface electric field and shunt impedance per unit length. Fig. 1 shows a plot of the ratio of the peak surface electric field, Ep, to the average axial accelerating electric field, Eo, vs. shunt impedance per unit length for a given beam hole diameter and web thickness. The figure clearly shows the tradeoff situation between the peak electric field and shunt impedance. The optimized shunt impedance with the constraints used (constant beam hole diameter and web thickness) appears to reach a limit of about 130 MΩ/m with Ep/Eo values of 8 or higher.

Table I

	Cavity I	Cavity II	Cavity III
Frequency (MHz)	2997	2997	2997
ZT^2/L (MΩ/m)	104.0	117.1	130.2
E_p/E_o	3.61	6.04	8.08
Qtheor	18520	18411	16835
l (m)	0.025	0.025	0.025
Qexp (half cavity)	7780	7310	6670
Zeff (half cavity)	43.7	46.5	51.6
P_t (MW)	2.52	1.02	0.45
E_o (MV/m)	66.3	43.6	30.5
Emax (MV/m)	239.4	263.1	246.4

(Note) Operating Condition
Pulse Width = 4.4 μsec
Repetition Rate = 200
Cavity Starting Pressure = 2 x 10^{-7} mmHg
Cavity Surface Finish = 8 microinch

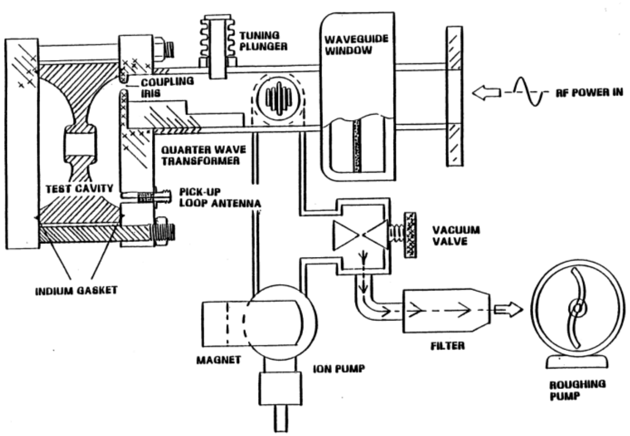


Fig. 2 A cross sectional view of the cavity test system.

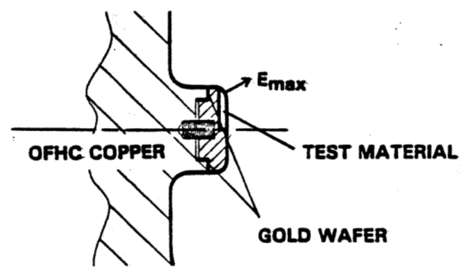
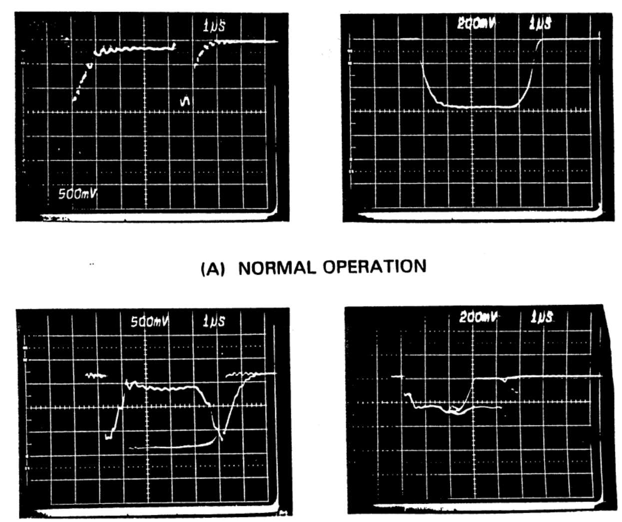


Fig. 3 Design of demountable nose button and position of Emax.



(A) NORMAL OPERATION

(B) BREAKDOWN LEVEL

Fig. 4 Reflected and transmitted RF power

Voltage Breakdown at MW Frequencies

VOLTAGE BREAKDOWN AT X-BAND AND C-BAND FREQUENCIES

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Palo Alto, California 94303

J. W. WANG and G. A. LOEW
Stanford Linear Accelerator Center
Stanford University, Stanford, California 94305

Summary

Economy of length and electric power in the design of future linear accelerators requires a knowledge of the electric field breakdown limits in RF structures as a function of frequency. The limits predicted by the Kilpatrick breakdown criterion, which gives a law of maximum surface electric field increasing with frequency, have already been exceeded at frequencies under 1 GHz and S-band (3 GHz). The work described here explores these limits at 5 and 9 GHz in single cavities. Experimental setups, procedures and results are presented.

Introduction

In the design of high gradient accelerator structures (accelerating gradients over 100 MV/m) for high energy physics linear colliders, or for medical and industrial applications where space is limited, voltage breakdown becomes a major constraint. Recently, the authors of this paper have separately conducted a series of breakdown experiments at S-band frequencies and have obtained maximum surface electric fields in excess of 300 MV/m for a few μsec pulsed operation.[1,2] These results indicate that the maximum surface electric field for well prepared OFHC copper in a clean environment can exceed six times the "Kilpatrick breakdown criterion."[3] It is of interest to investigate the breakdown threshold level at even higher frequencies since the criterion states that the maximum field increases with the operating frequency. Moreover, there are other advantages of using higher frequencies for accelerators, i.e., higher shunt impedance per unit length, smaller diameter, and shorter filling time.

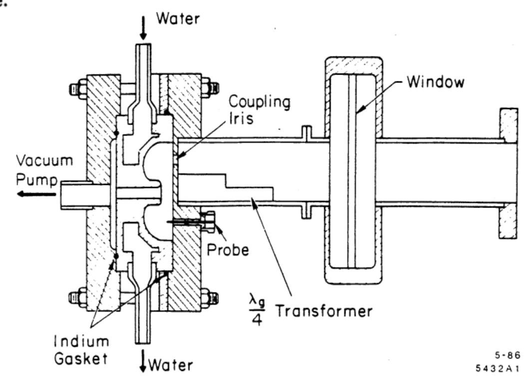

Fig. 2. A cross-sectional view of the C-band demountable, single-cavity tester.

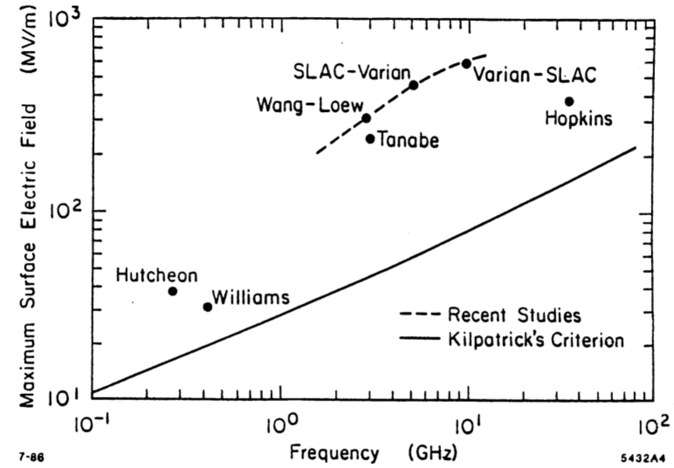

Fig. 1. Kilpatrick breakdown criterion and some experimental results.

Table 2. Field Calculated for Normalizing Conditions
$|\int_0^L E_z(z)\exp^{j(\omega z/c)}\,dz\,|/L = 1$ MV/m

	C-Band	X-Band
Resonant frequency, f	4998	9303
Q (half single cavity, including end plate)	7018	5595
r/Q per unit length	113.3 Ω/cm	158.8 Ω/cm
Energy stored, W	3.915×10^{-5} J	7.205×10^{-6} J
Power dissipated, $P_D=\omega W/Q$	176.8 W	76.26 W
Maximum surface field, E_{max}	7.542 MV/m	4.876 MV/m
Average accelerating field, $\bar{E}_{acc}$	0.966 MV/m	0.908 MV/m
$E_{max}/\bar{E}_{acc}$	7.81	5.37

Microwave Gun

A 2-MeV MICROWAVE THERMIONIC GUN†

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‡ AET Associates, Cupertino, CA 95014, USA
* Sta··ford Synchrotron Radiatic . Laboratory, Stanford University, Stanford, CA 94309, USA
§ Varian Associates, Palo Alto, CA 94303, USA
° Stanford Linear Accelerator Center, Stanford University, Stanford, CA 94309, USA

ABSTRACT

A high-gradient, S-band microwave gun with a thermionic cathode is being developed in a collaborative effort by AET, Varian, and SSRL. A prototype design using an upgraded Varian dispenser cathode mounted with thermal isolation directly in the first half-cell of a 1-1/2 cell, side-coupled, standing-wave cavity has been fabricated and is being tested. Optimization of the cavity shape and beam formation was done using SUPERFISH, MASK, and PARMELA. An overview of design details, as well as the status of in-progress beam tests, will be presented.

INTRODUCTION

In a collaborative effort, AET Associates, Varian Associates (VA) and the Stanford Synchrotron Radiation Laboratory (SSRL) are developing a 2 MeV S-band microwave electron gun. In one application it would be an integral part of a VA medical or radiographic accelerator. In another application it would be part of a SSRL pre-injector for SPEAR as a synchrotron light source. In the first case simplicity and compactness are the design criteria. The goal is to be able to mount a cathode directly in the first half cell of a standard VA side-coupled, standing-wave accelerator section. Thus, the normally-used 20 kV gun insulator and pulse-transformer winding would be eliminated, but cathode thermal isolation and back-bombardment heating problems might be substituted. In the second case, a 1-1/2 cell (plus one side-coupling cell) microwave gun will generate a train of bunches that will be compressed in time by an alpha magnet and narrowed in energy spread by slits built into the alpha magnet. A fast, FET-switched chopper-collimator at the entrance to a 150 MeV linac will allow selection of three bunches out of the several thousand that are produced over a range of energies and during several microwave gun cavity fill times.

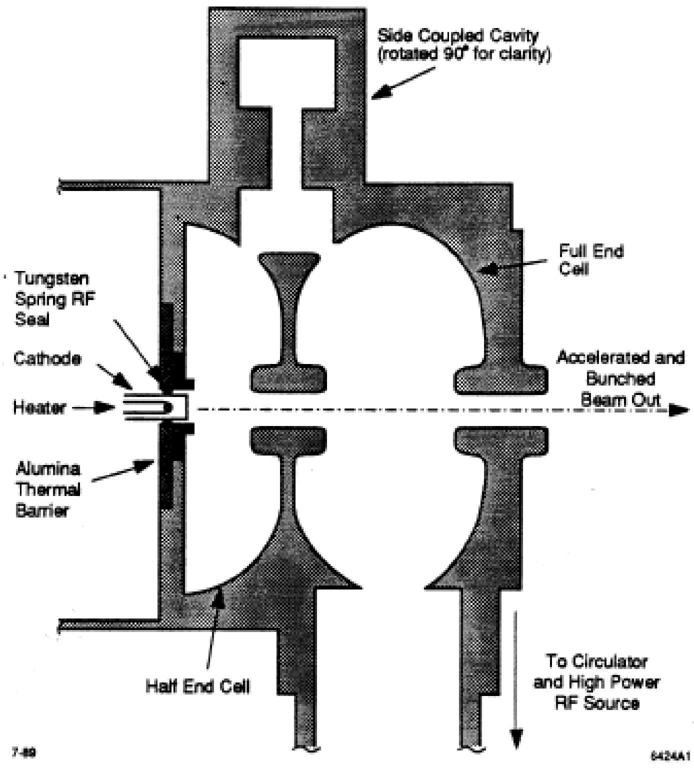


Fig. 1: Cross-sectional view of the 1-1/2 on-axis cells.

copper-plated (~ 0.01 mm). RF contact between the stem and the barrier is made via a tungsten-wire spring in the form of a

Higher Shunt Impedance at Low Temp.

High Gradient Accelerator Cavities

At Liquid Nitrogen Temperature

Eiji Tanabe, Albert H. McEuen, and Matthew Bayer
Varian Associates Inc., Palo Alto, California, U.S.A.

Abstract

It has been demonstrated in low power tests that the quality factor, Q of a microwave cavity made of copper is greatly increased by reducing the operating temperature to that of liquid nitrogen. Recently, two S-band cavities of different geometries were tested at liquid nitrogen temperature. The experimental results show that the increase in Q at low temperature was much less at high power levels than at low power levels. Furthermore, Q is a function of the peak power of the microwave pulse, rather than the average power level. In this paper, these experimental results are presented, and possible methods for optimizing the cavity geometry and processing to minimize this effect are discussed.

Introduction

The obvious advantages of the use of superconducting materials in particle accelerators have been explored extensively over the past 25 years[1,2]. However, the cost of constructing and operating the refrigeration systems necessary to maintain the low temperatures required[3,4] limits consideration of this approach to large, well-funded research projects.

An alternative worthy of investigation is accelerators constructed of conventional materials, operating at temperatures attainable with more conventional refrigeration systems of moderate cost. The conductivity of metals suitable for use in accelerators increases at low temperatures. Therefore the efficiency of a guide structure constructed of copper, for instance, can be increased by reducing its operating temperature.

The microwave surface resistivity of OFHC copper decreases by a factor of at the temperature of liquid nitrogen (-197°C)[5]. Considering the availability of this refrigerant and the modest cost of packaged cryogenic systems capable of maintaining this temperature, one might expect that an accelerator system operating under these conditions would prove advantageo for some applications. In particular, in situations where the space avail for the accelerator structure is limited, or where there is a limitation o the RF power available, this might be considered.

In order to evaluate the advantages and problems associated with a system operating at liquid nitrogen temperature, a limited investigation was undertaken at Varian with the following two objectives: first, to establ the feasibility of operating an accelerator structure at -197°C, and secon to determine what advantages might be realized with respect to size or pow input requirements.

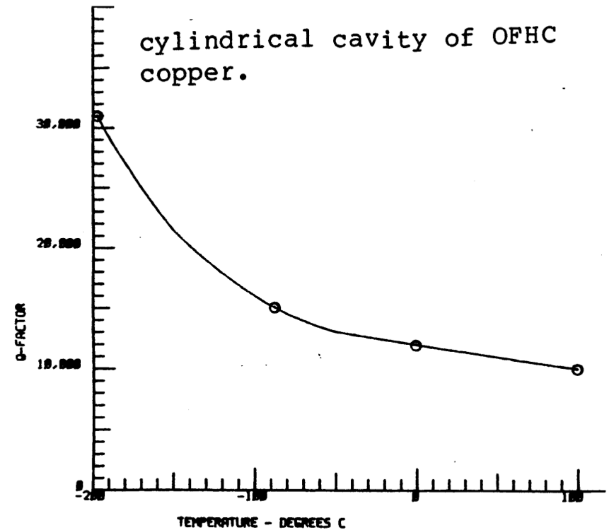


Fig. 1 Variation of Q-factor with temperature.

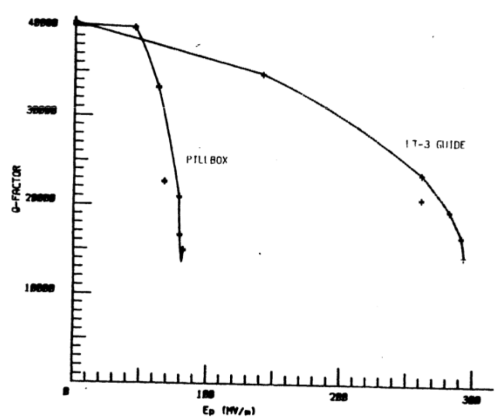


Fig. 4 Q-factor vs peak RF electric field at -197°C.

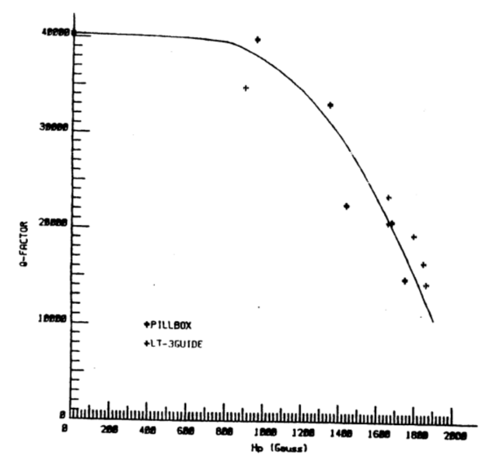
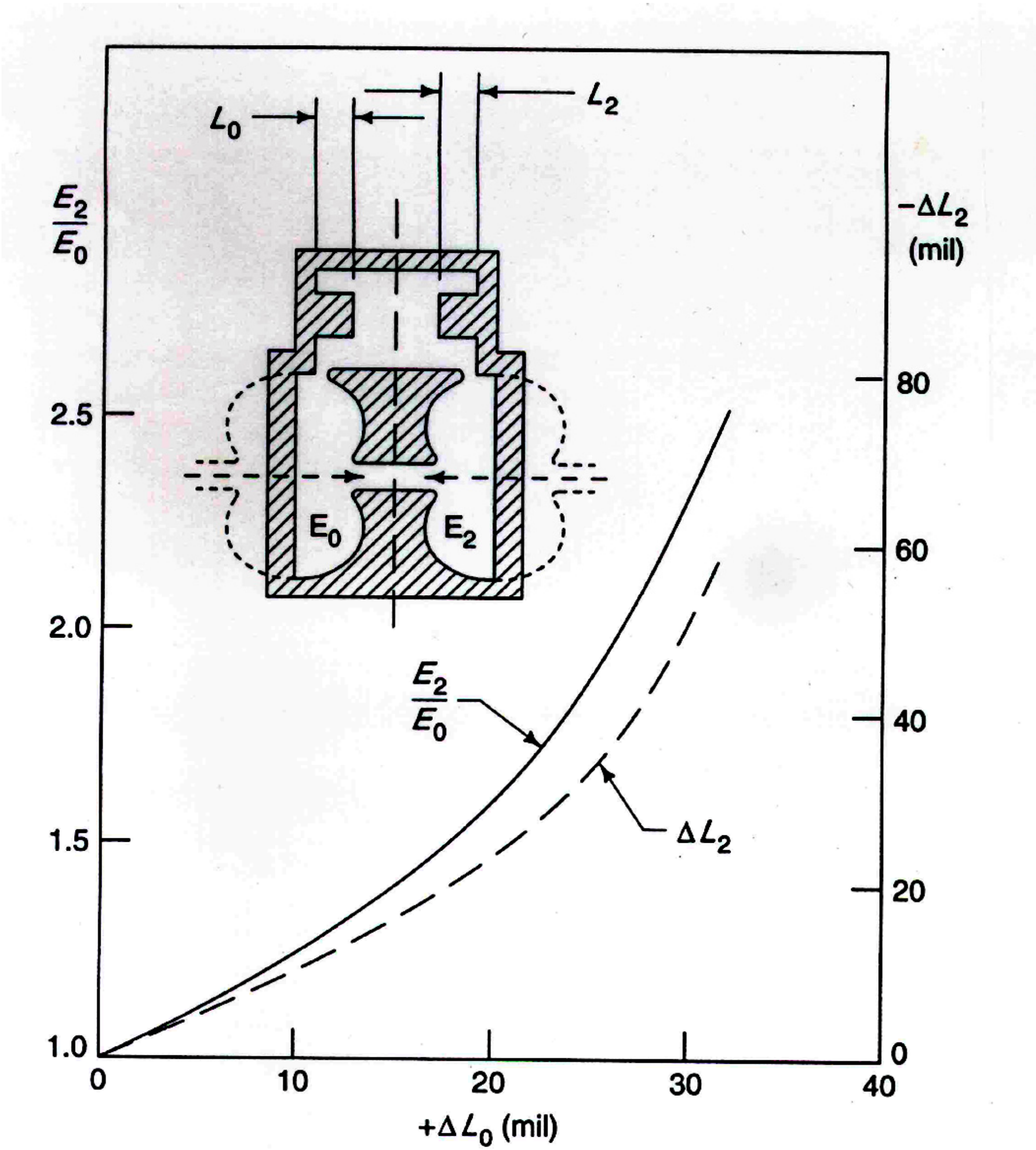


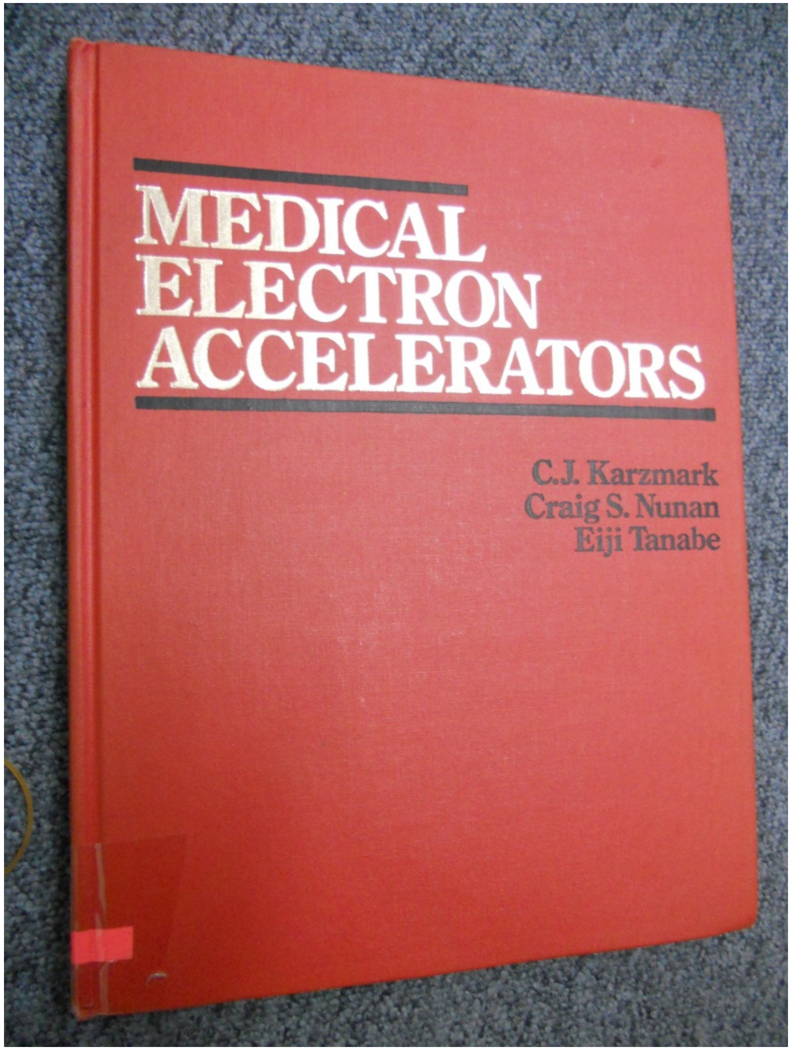
Fig. 5 Q-factor vs peak RF magnetic field at -197°C.

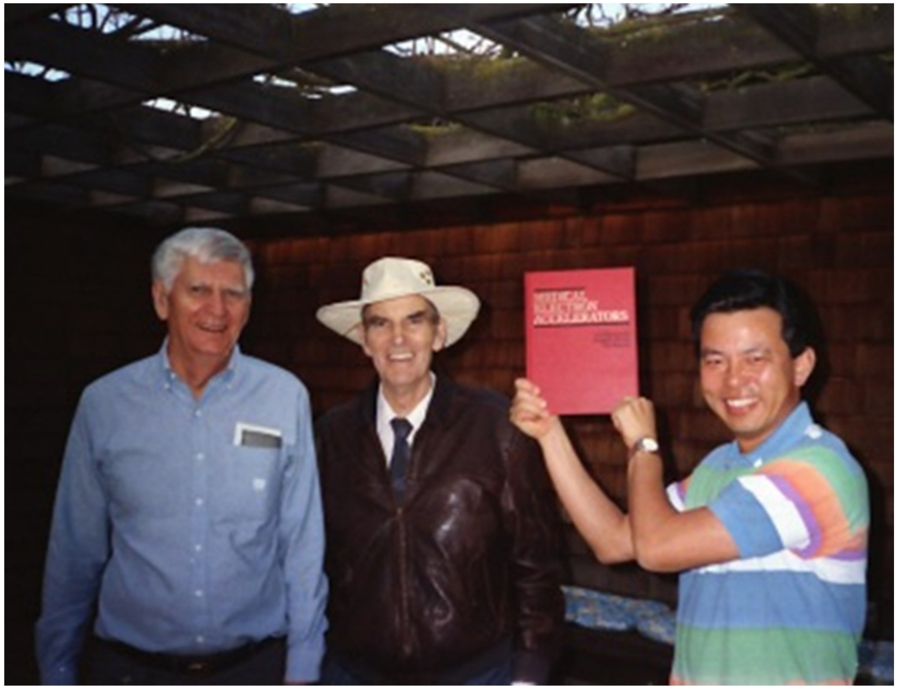
Variable Side Coupling Structure



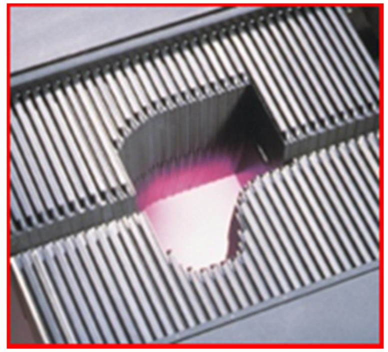
Multi-Energy Medical Linear Accelerator

Book of "Medical Electron Accelerators"





Evolution of Radiation Therapy System



Accelerator R and D
Verification Study
1960s

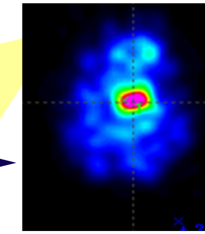
Higher Energy and E-Beam
System Development
1970s

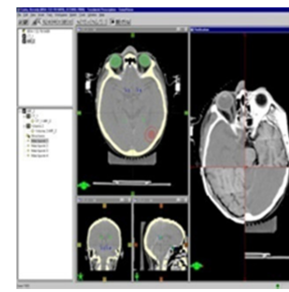
Dual Photon Energy and
Computerization
1980s

Dynamic Therapy and
Software
1990s

Systemization and
Process
2000s

Imaging and Motion
Management
2010s

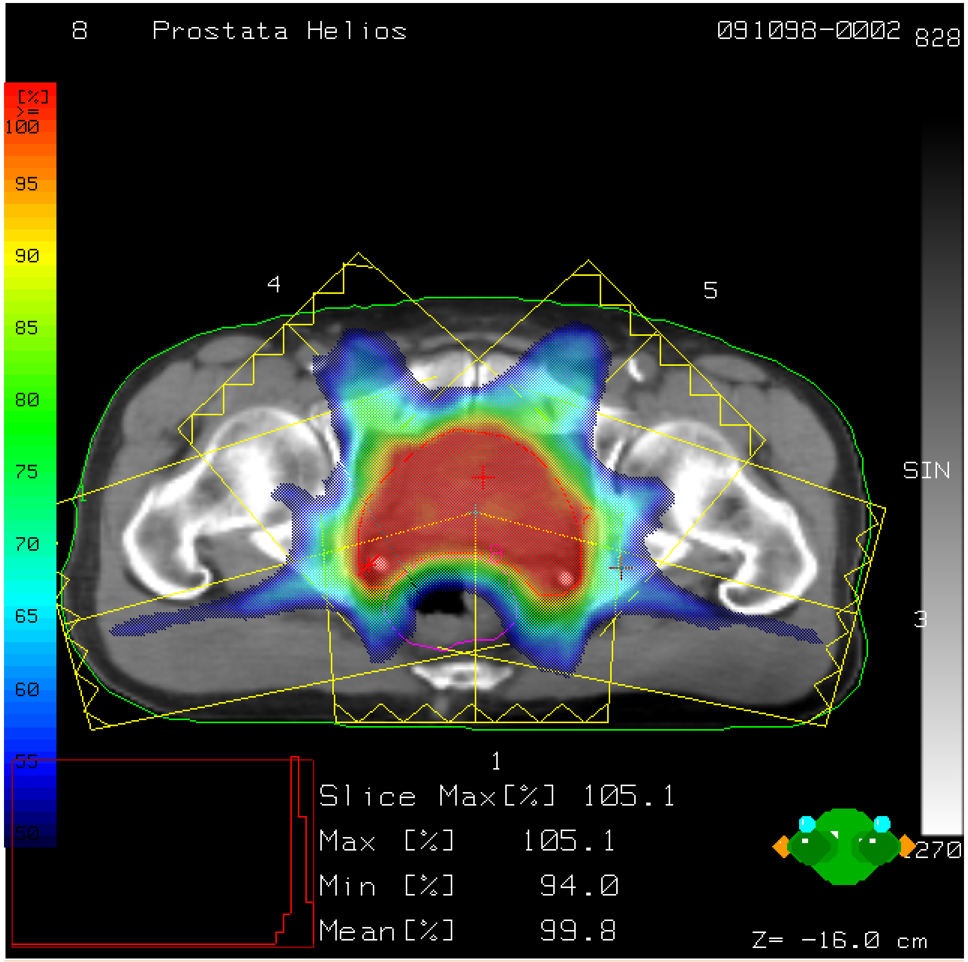




Computerized 3D CT Treatment Planning

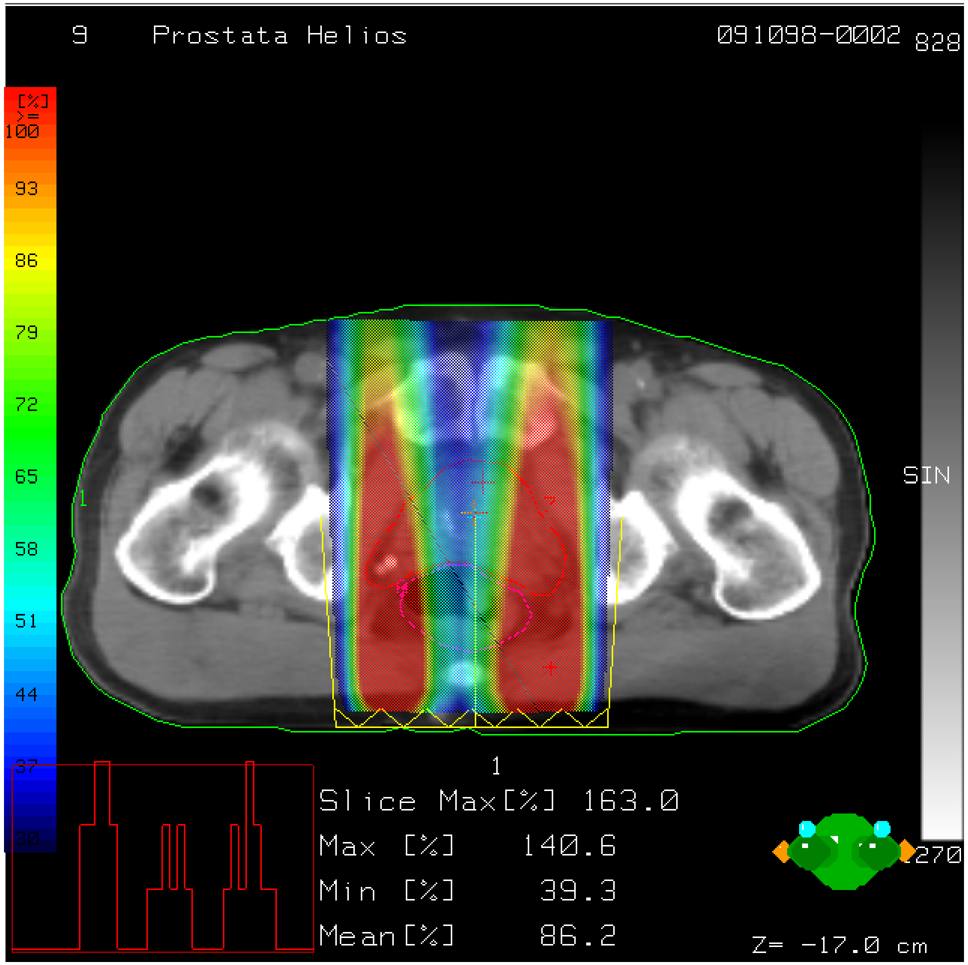
Advances in Radiation Therapy Technology

Prostate Treatment(Intensity Modulated RT:IMRT)



Advances in Radiation Therapy Technology

Prostate Treatment (Intensity Modulated RT:IMRT)



Advances in Radiation Therapy Technology

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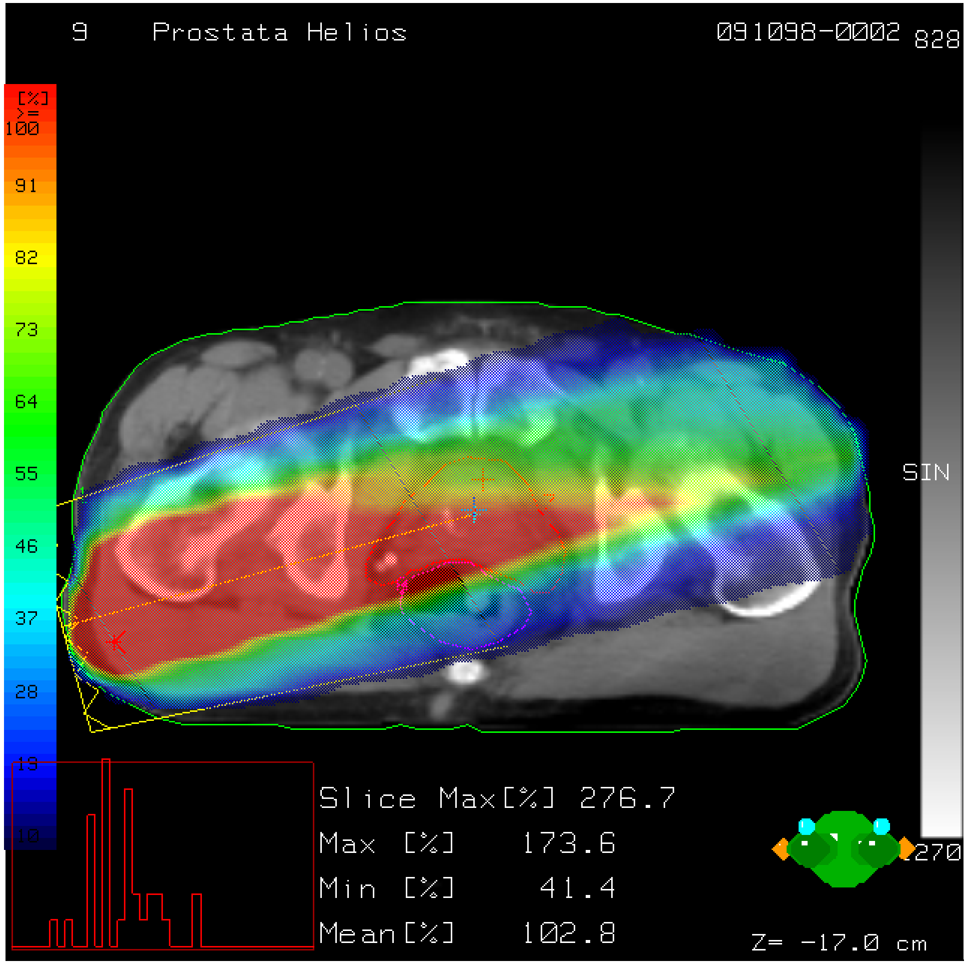
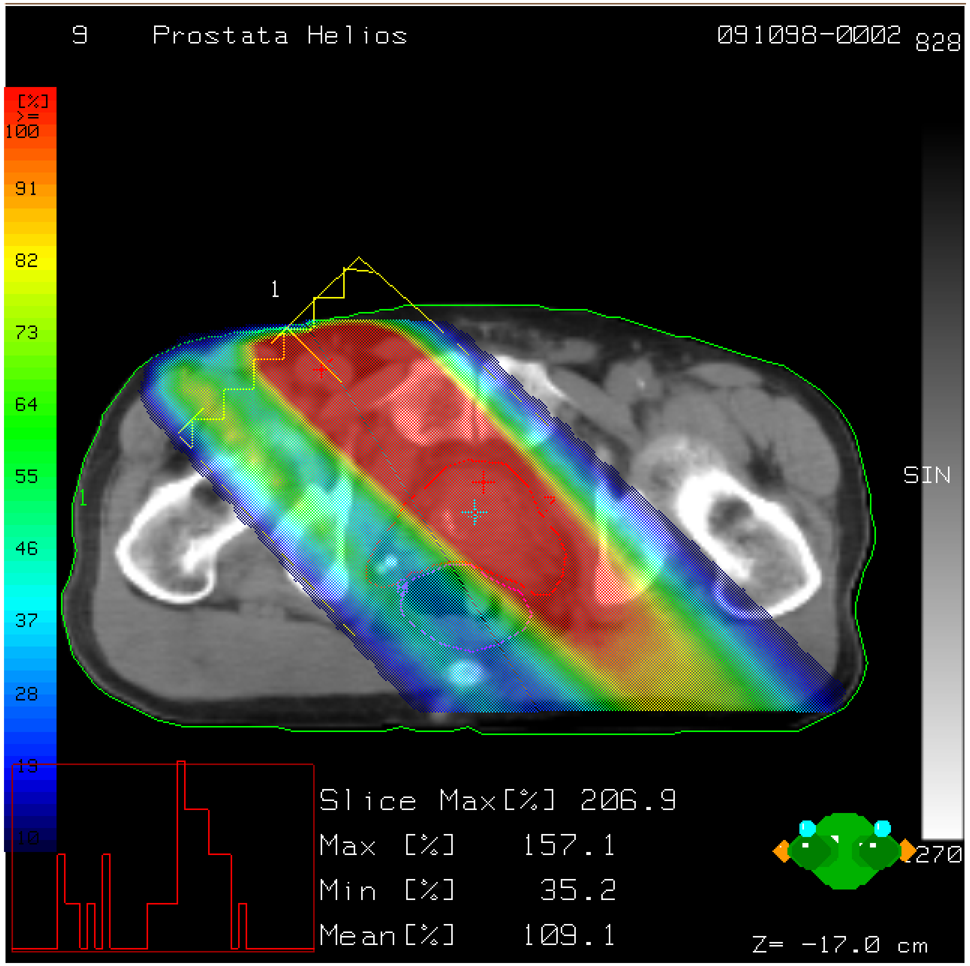
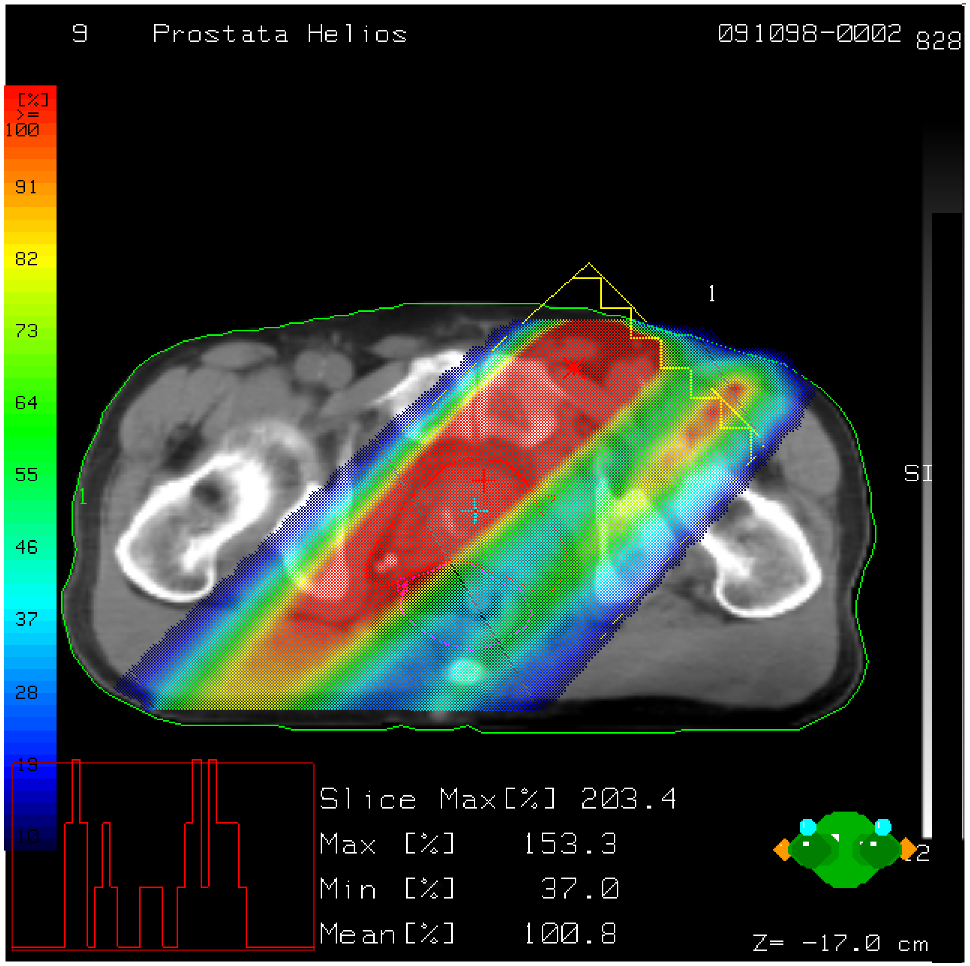


Prostate Treatment(Intensity Modulated RT:IMRT)



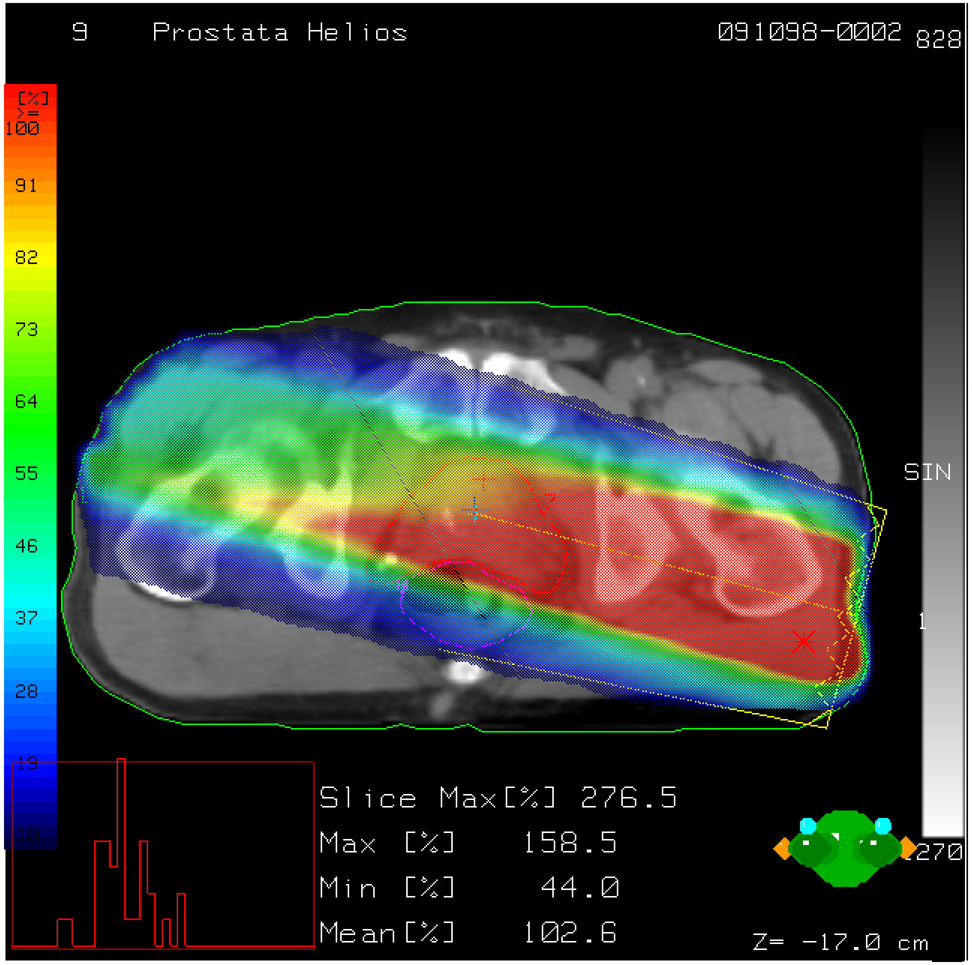
Advances in Radiation Therapy Technology

Prostate Treatment (Intensity Modulated RT:IMRT)



Advances in Radiation Therapy Technology

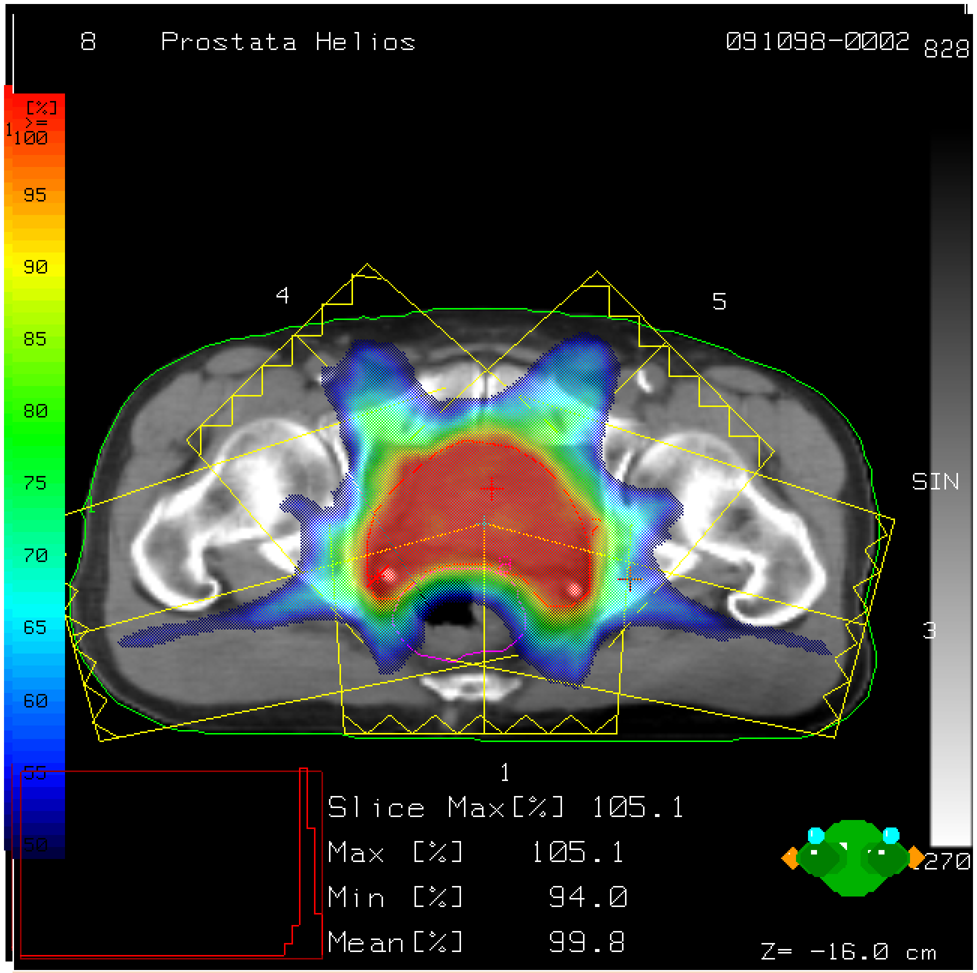
Prostate Treatment（Intensity Modulated RT:IMRT）



ACCUTHERA

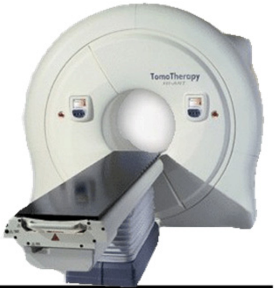
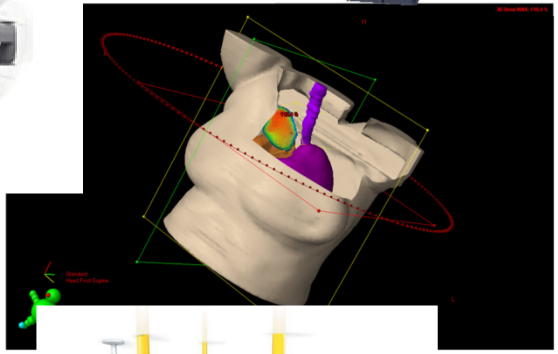
Advances in Radiation Therapy Technology

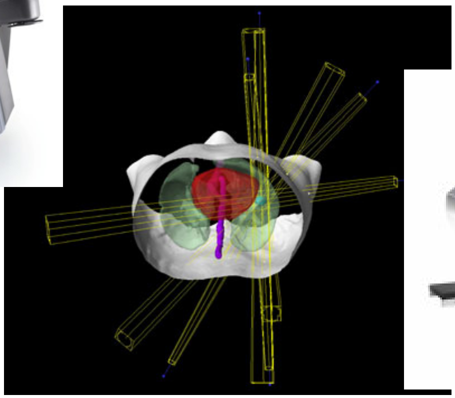
Prostate Treatment (Intensity Modulated RT:IMRT)



Stereotactic Body Radiation Therapy

- Not a machine, but a type of radiation delivery.
- <u>*Stereotactic*</u> = precise positioning of the target volume in 3 dimensions.
- Has become synonymous with high dose per fraction.
- Different delivery techniques (arcs, static fields, protons)

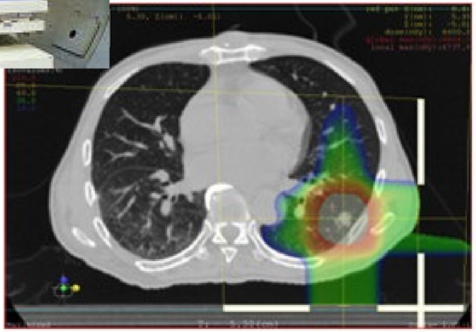
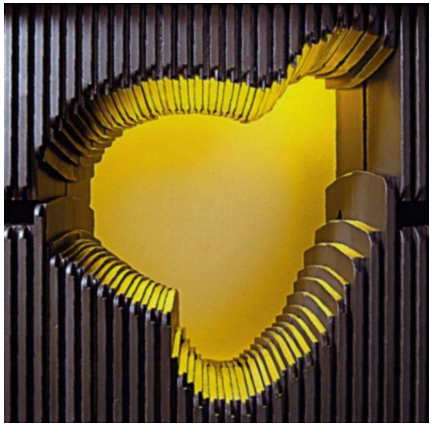



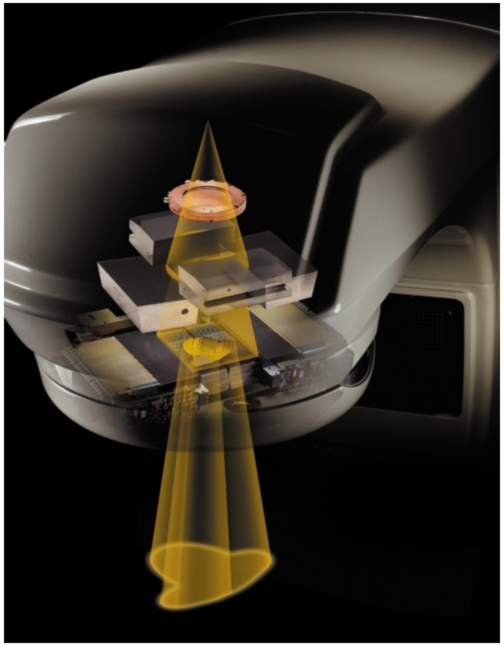
Image Guidance / Delivery Technology

1. Single X-ray tube added to delivery unit
2. Dual X-ray tubes and flat panels w or w/o fiducial markers
3. Ultrasound/CT matching with video image referencing
4. 3D Surface Alignment
5. Implanted fiducial markers with RF localization
6. CT on Rail
7. MV Portal Imaging
8. Multiple Fluoroscopic systems
9. CT + Simulator + Accelerator
10. Cone Beam CT on Accelerator
11. Digital Tomosynthesis
12. Megavoltage CBCT
13. Helical Tomotherapy with MVCT
14. Movable X-ray head with integrated CBCT
15. CT/Pet Systems
16. Integrated MRI imaging and radiation delivery

Technologies required for Future RT

IMRT, IGRT,
SRS, SRT
Adaptive RT,
Cone Beam CT,
Portal Vision,
KVXR................





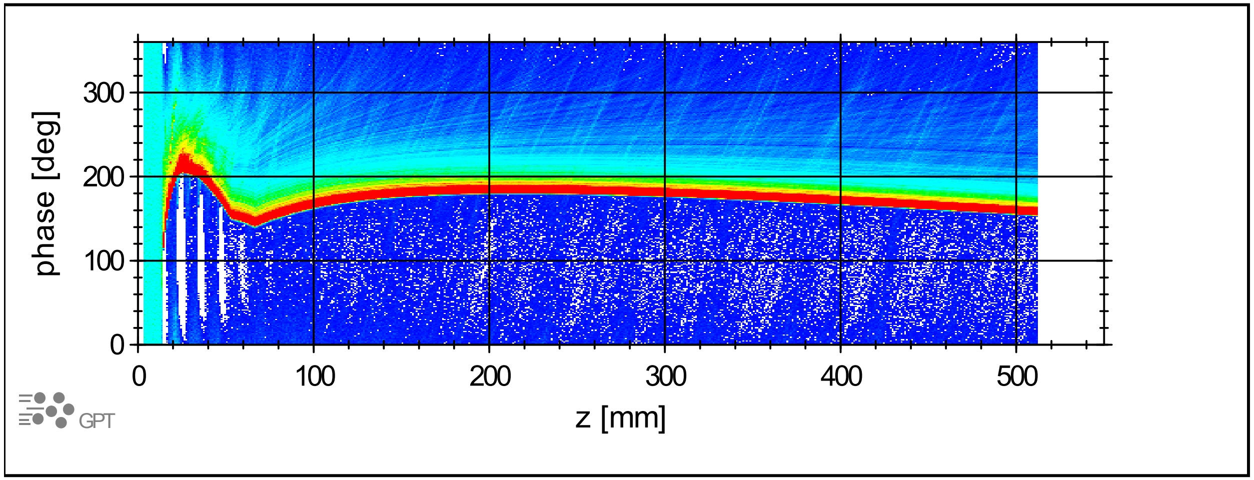
High Dose Rate
High Accuracy in Space and Time
Real Real Time
Higher Stability
Higher Efficiency
Higher Freedom

Compactness
Light weight
Lower Cost
Automatic System
Lower Leakage
Maintenance Free

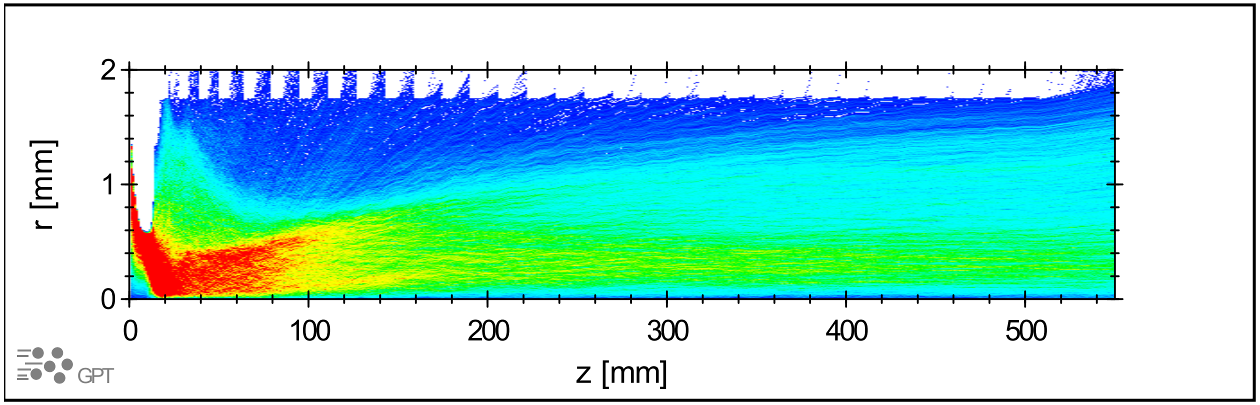
Medical Accelerator Core Technologies

- Electron and Ion Beam Accelerator Technology
- Electron Gun, and Ion Gun Technology
- Numerical Simulation Technology
- HV Pulse Technology
- X-Ray Technology
- Vacuum Technology
- Robotics and Control Technology
- High Speed Signal Process Technology
- High Energy Photon Detection Technology
- Electromagnetics, and Microwave Technology
- Material, and Process Technology

Accelerator Beam Dynamics Simulation

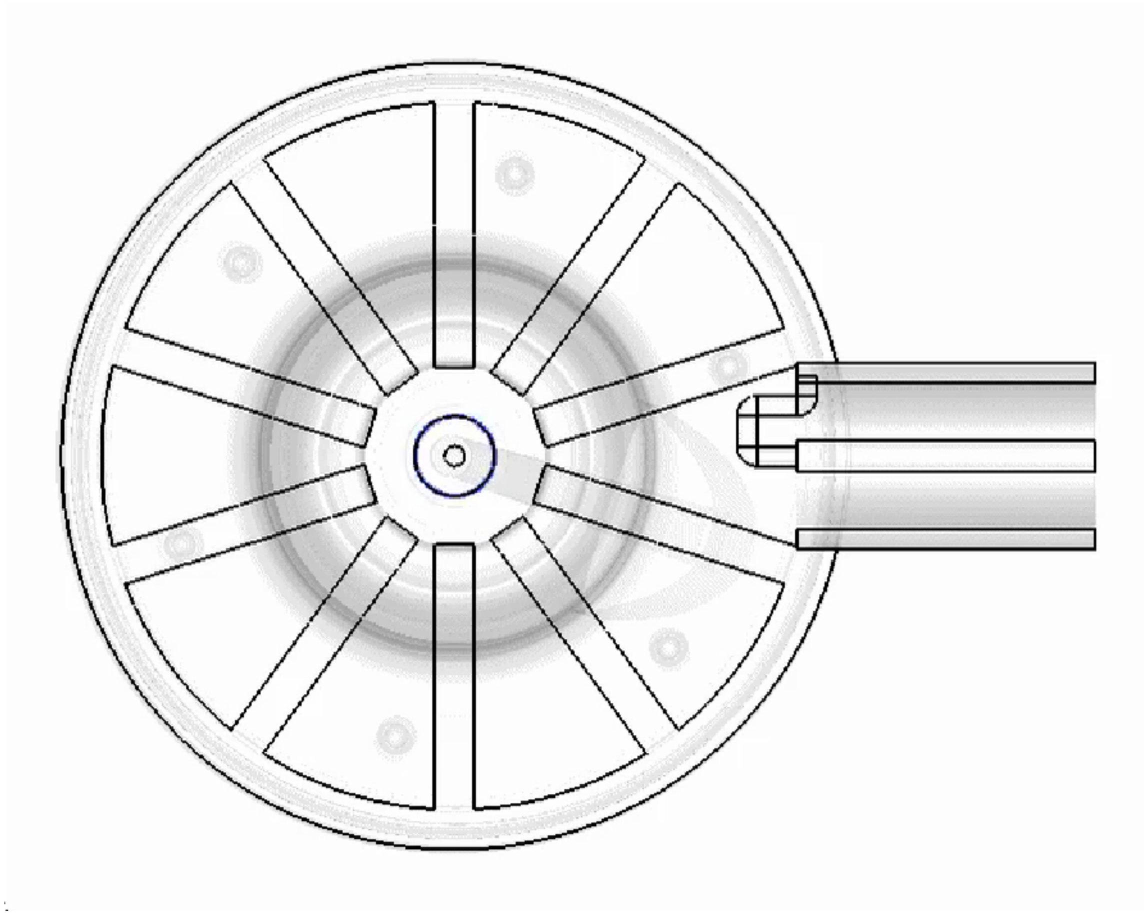


Phase Orbit Plot



Beam Radial Spread

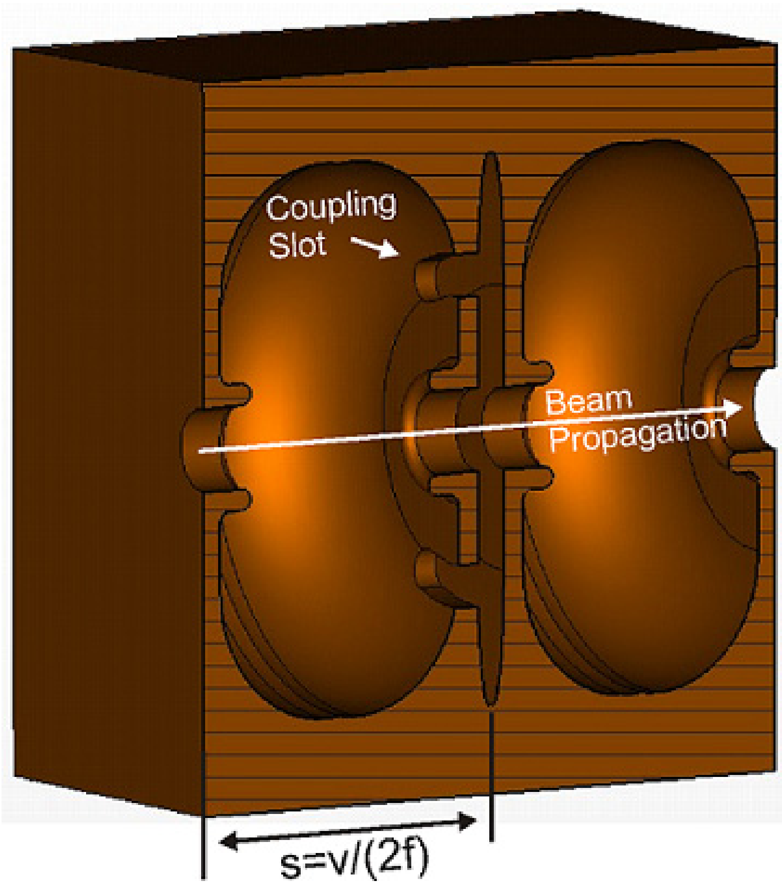
Magnetron Beam Dynamics

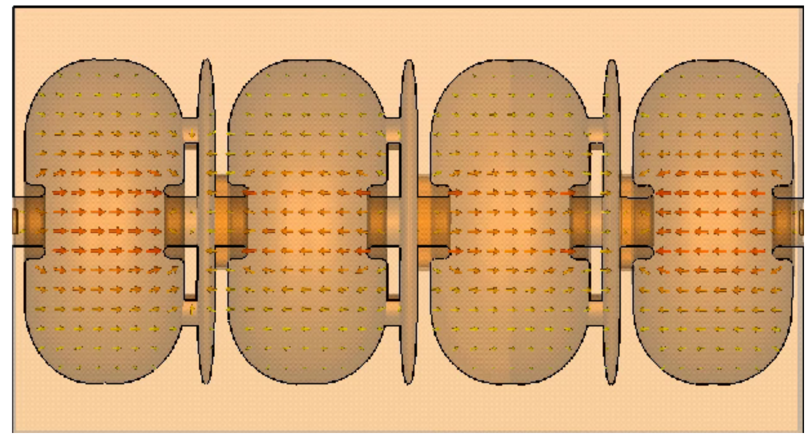


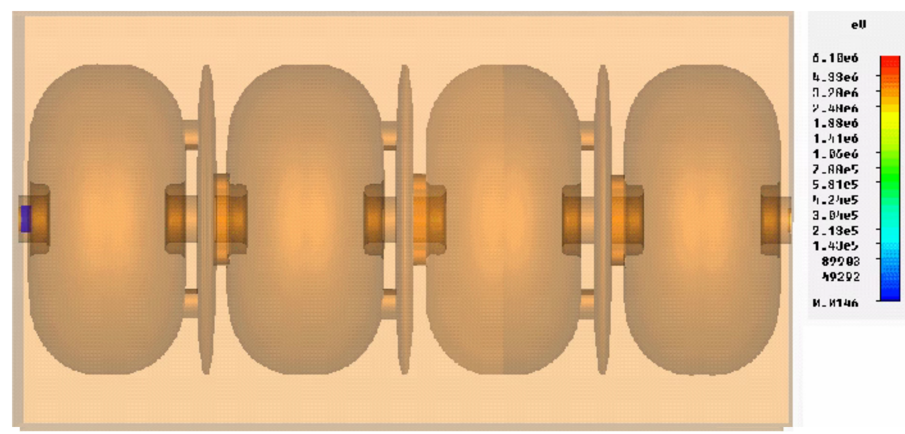
Spoke formation according to π-Mode

Rotating direction can be changed due to sampling artefact.

Accelerator Beam Dynamics

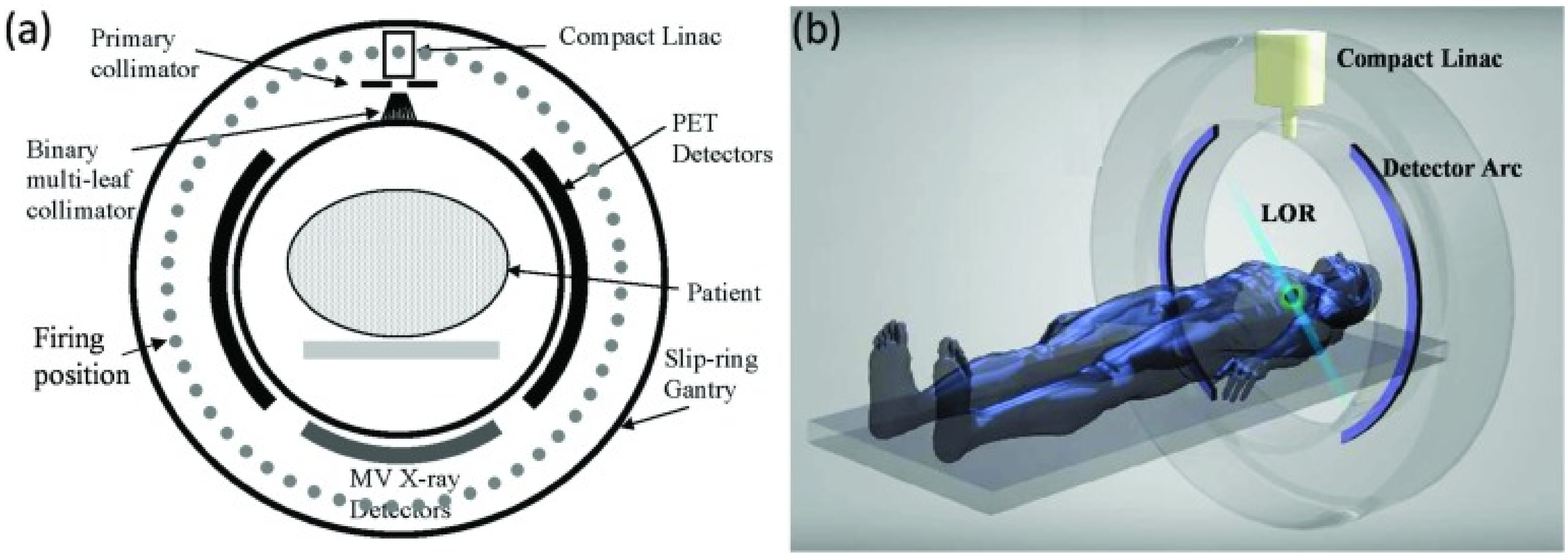




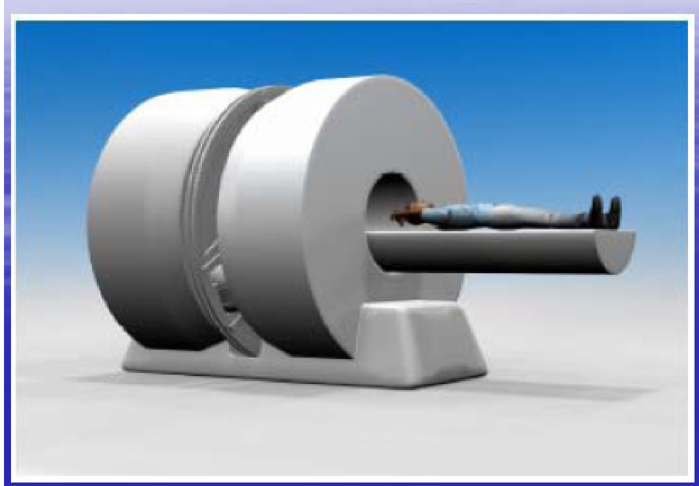


[1] Design, simulation and measurement conducted by M. Ruf, K. Thurn and L.-P. Schmidt at Chair for High Frequency Technology, University of Erlangen-Nuremberg

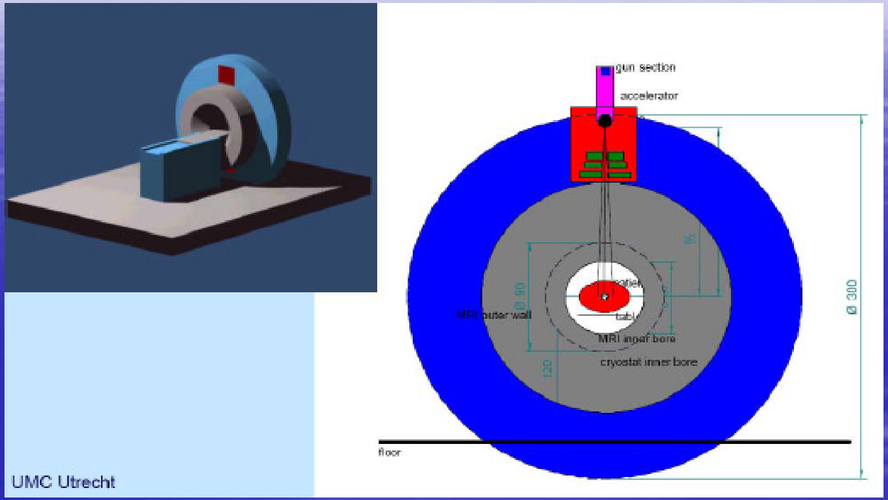
New Technology 1.
PET / CT and Linac by Reflexion



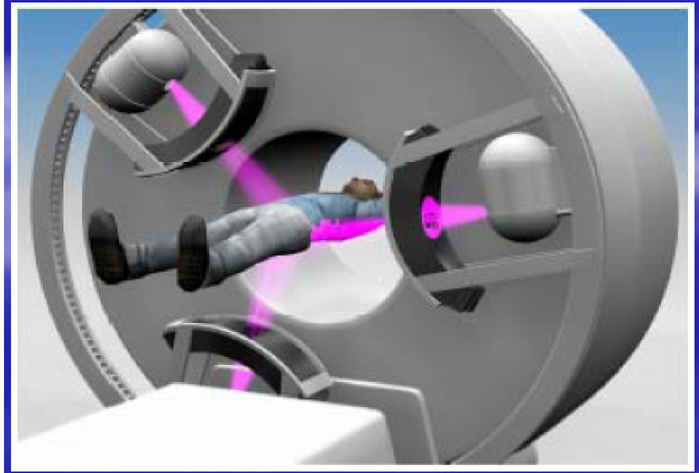
New Technology 2.
MRI and Gamma Radiation by ViewRay

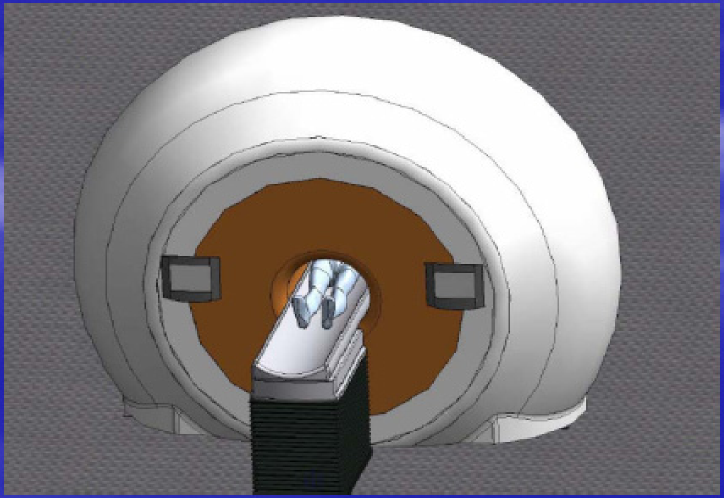


Renaissance™ System 1000
ViewRay Inc.



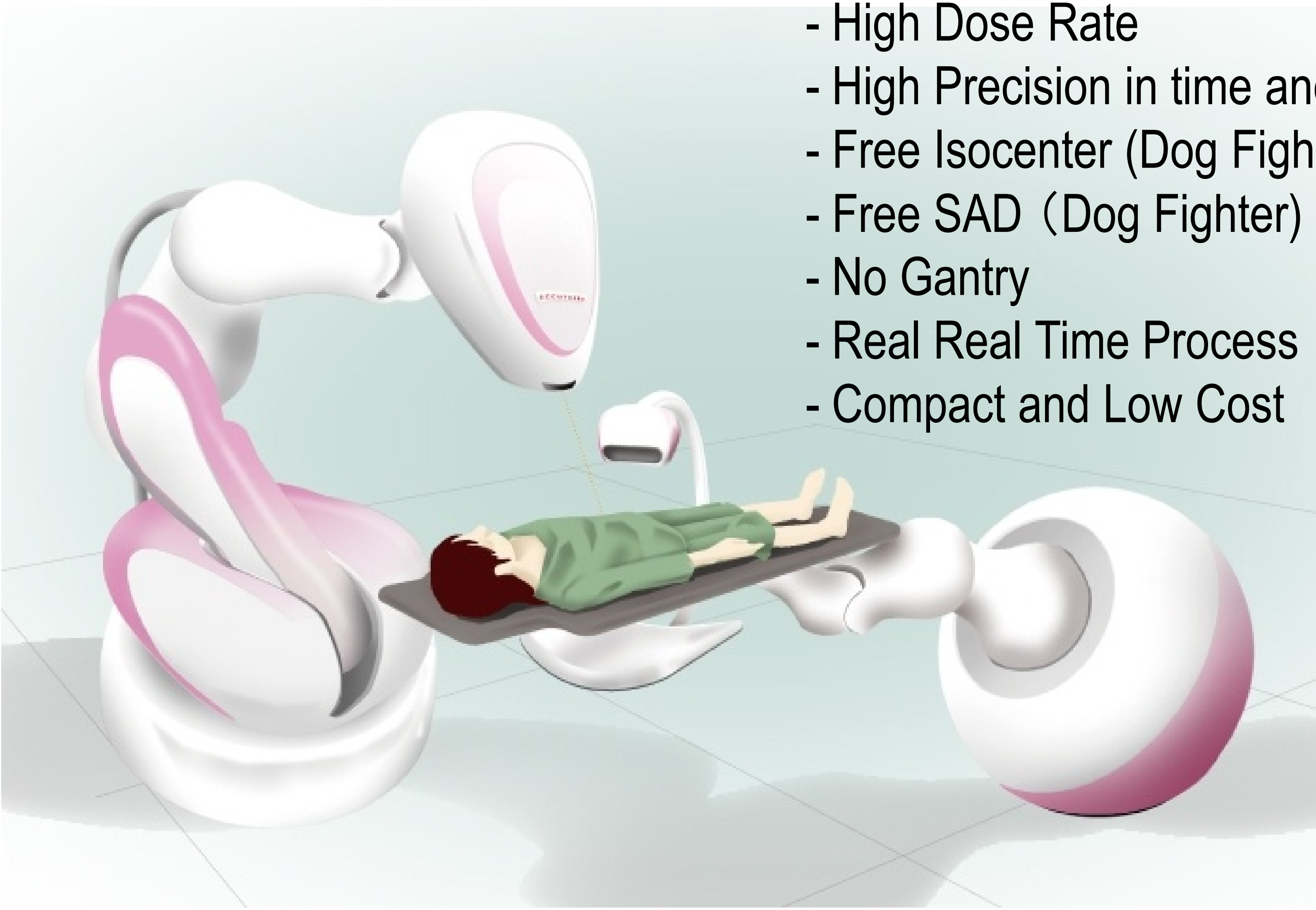
Artist concept of integrated MRI and Accelerator System





Ref:
In room MRI Guided Radiotherapy (MRIgRT)
Lagendijk, J. and Raaymakers, B., et al.
AAPM Jolint Imaging/ Therapy Symposium, In-room imaging for therapy guidance, 2005

Next Generation RT System Combined with Early Tumor Detection Technology

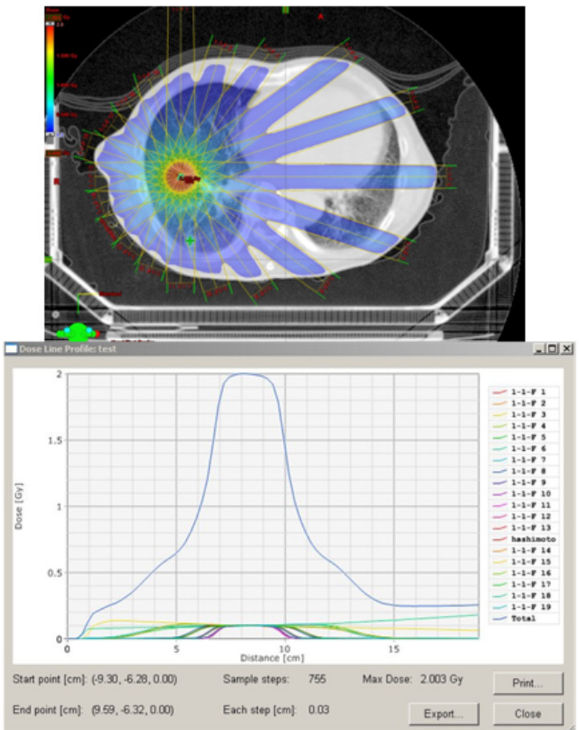


- High Dose Rate
- High Precision in time and Space
- Free Isocenter (Dog Fighter)
- Free SAD（Dog Fighter)
- No Gantry
- Real Real Time Process
- Compact and Low Cost

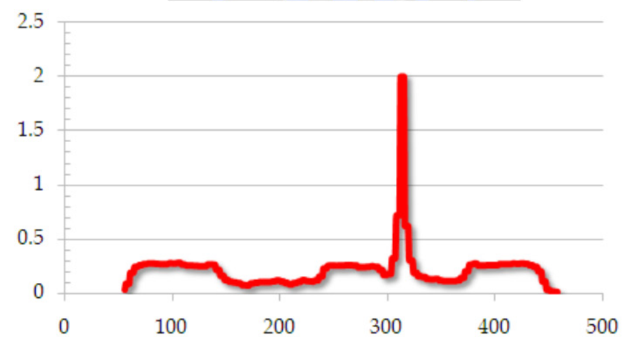
Narrow Beam Accelerator Technology

Narrow Beam vs Broad Beam

20 Broad Beam



20 Narrow Beam



Narrow Beam Technology provides a new RT with single high dose treatment and very low risk for early stage tumor

Robotic Moving Phantom with Robotic Accelerator and RTRT with Flat Panels

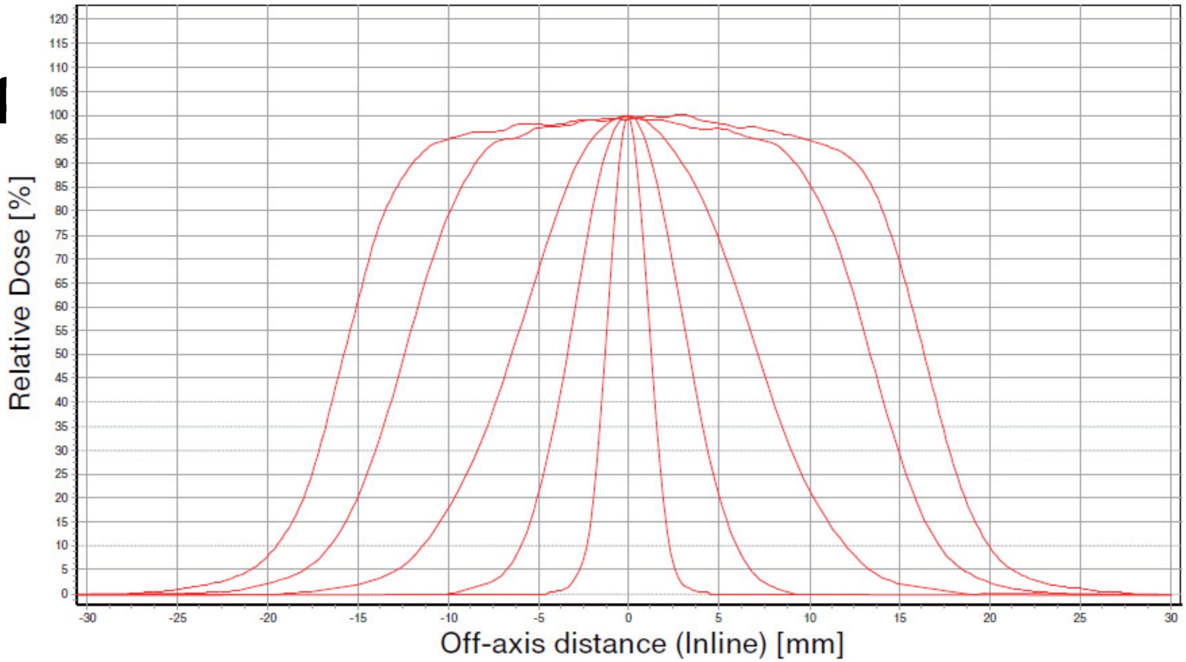
National Center for Global Health and Medicine

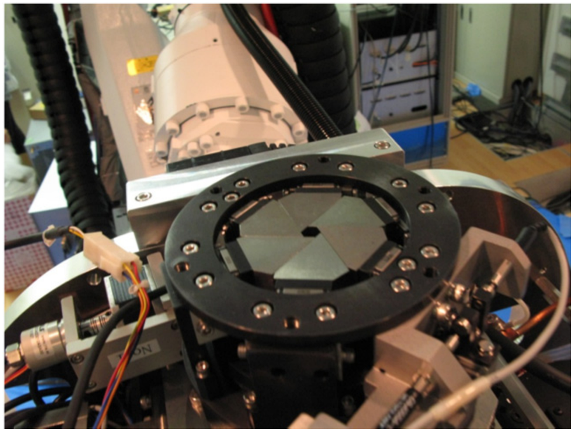
5:34
あす
栃木
24
14℃
がん治療が日帰りに!?
日本開発の"照射技術"
"日帰り"のがん治療

Dynamic Variable Collimator

■ **Size: 1mmφ～3cmφ**

Built In Variable Collimator



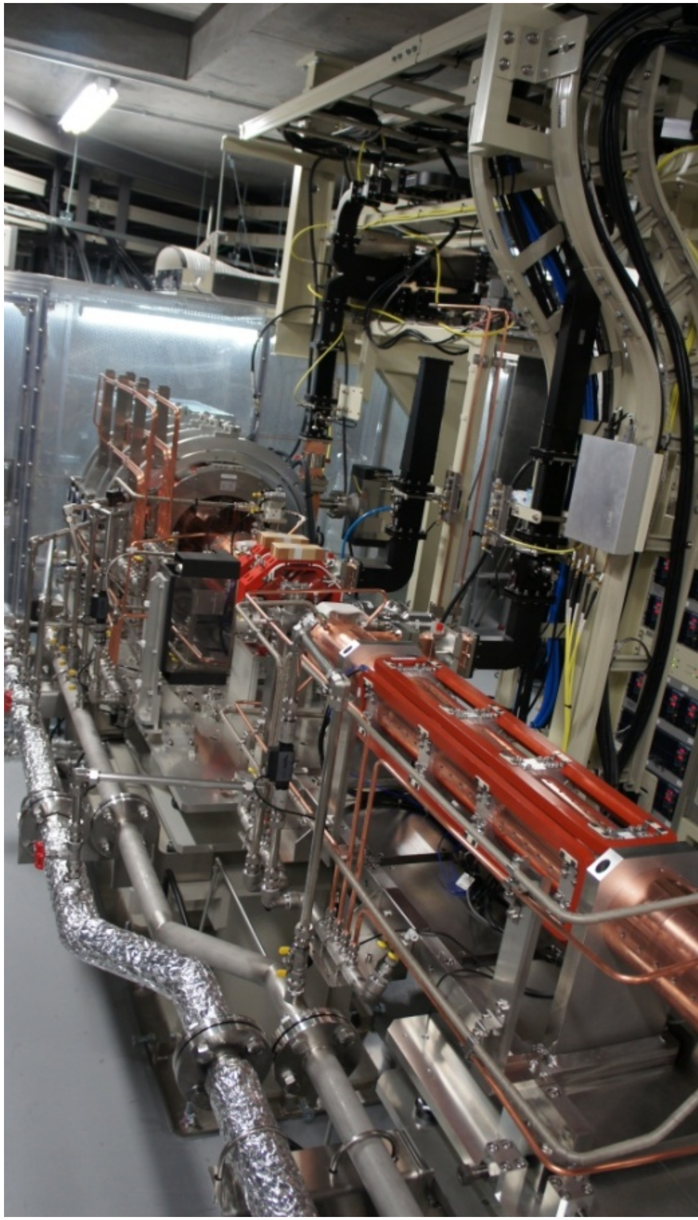


Fine painting requires different brush sizes and shapes!!

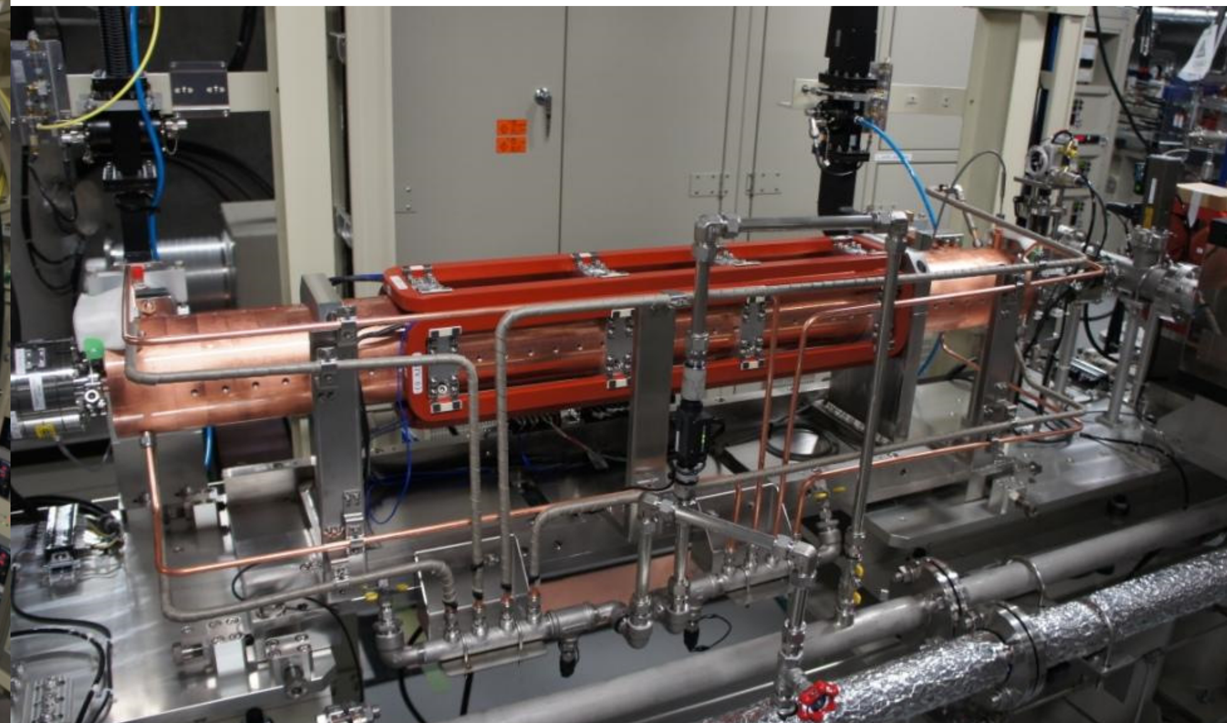
Electron Linear Accelerators for Industrial and Research Applications

- Electron beam materials processing
- Electron beam irradiators
- Radioisotope production
- Electron Microscope
- Non destructive testing and Inspection
- Neutron generators
- Synchrotron radiation

50 MeV Synchrotron Injector System

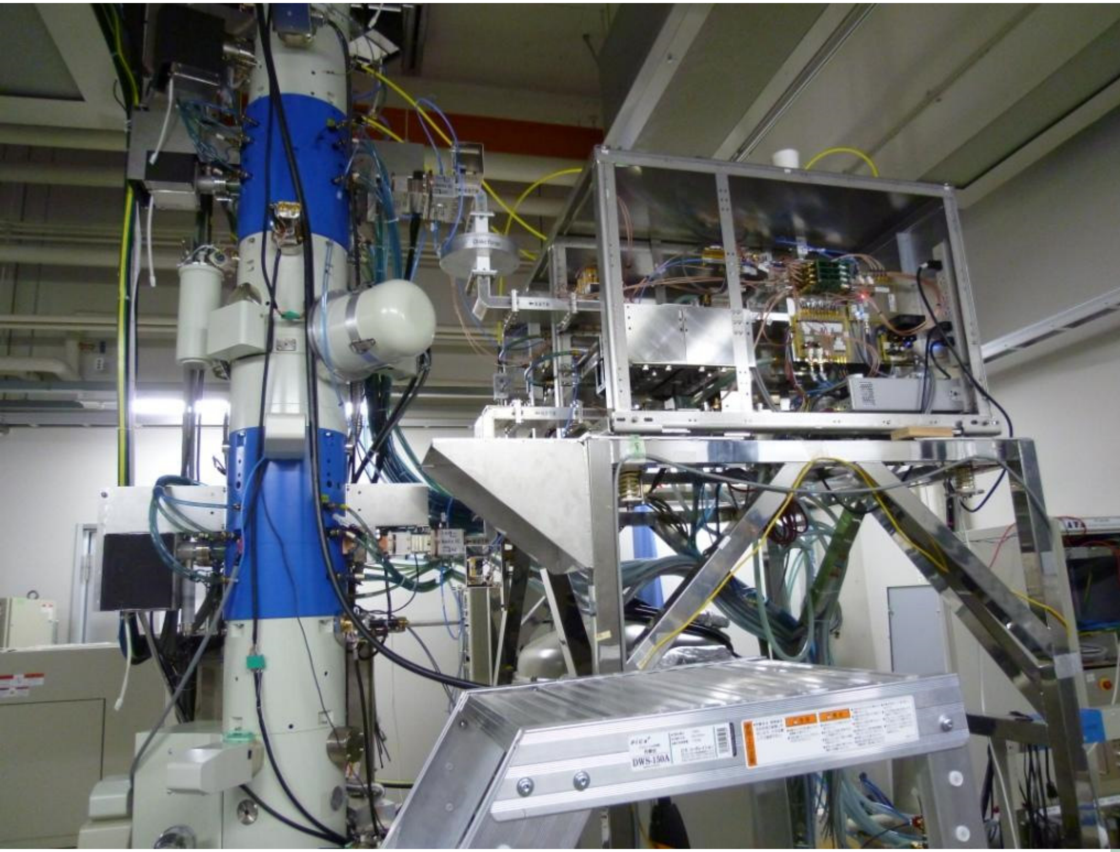


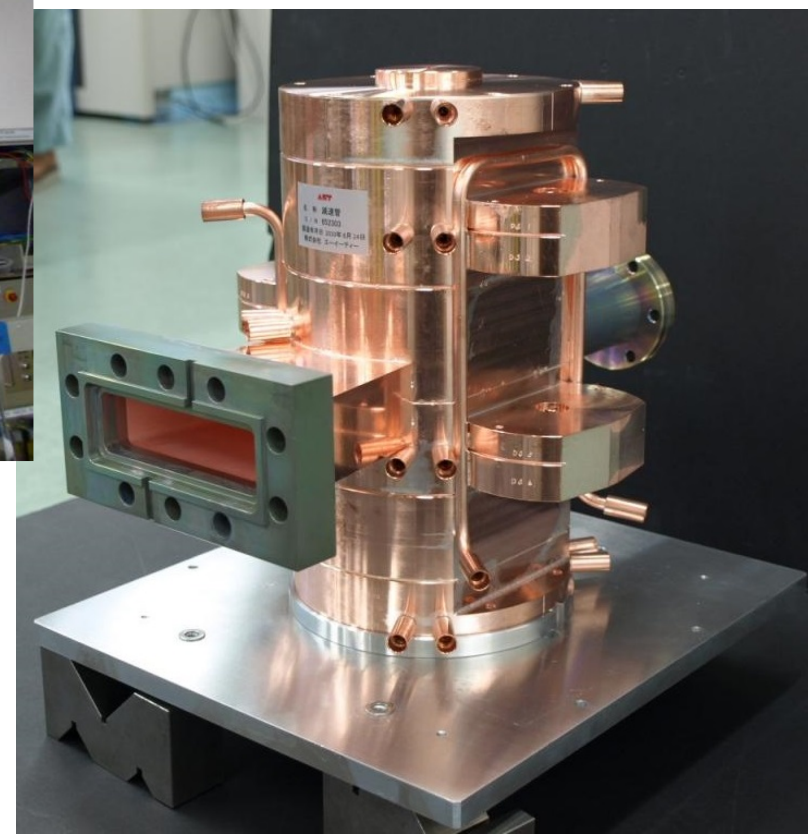
Nagoya Synchrotron Research Center



2856 MHz Traveling Wave Accelerators

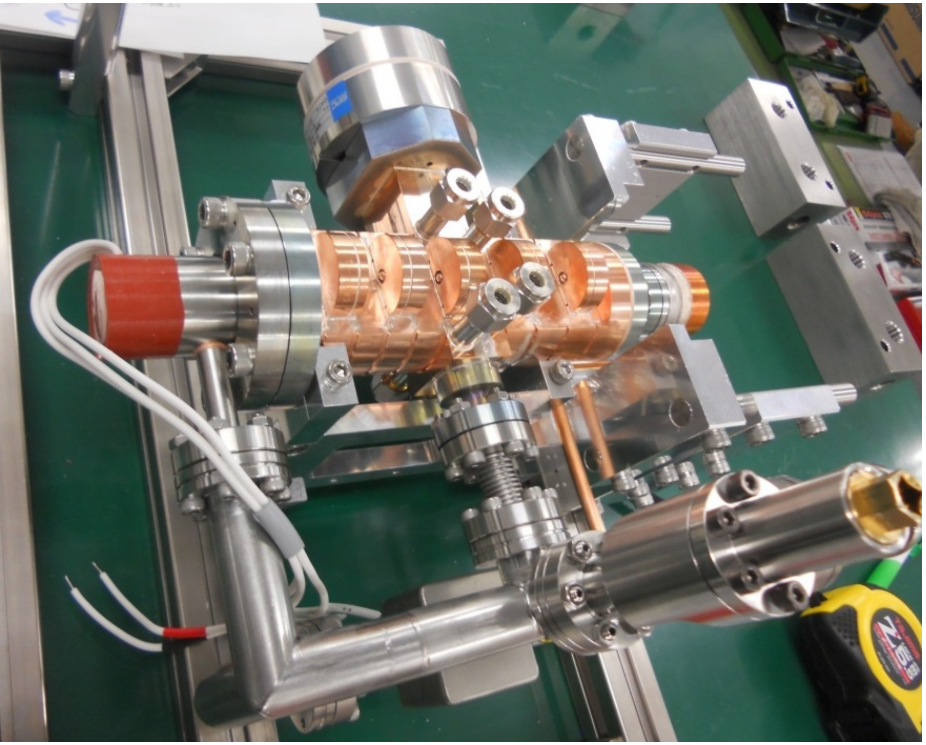
Microwave Electron Microscope





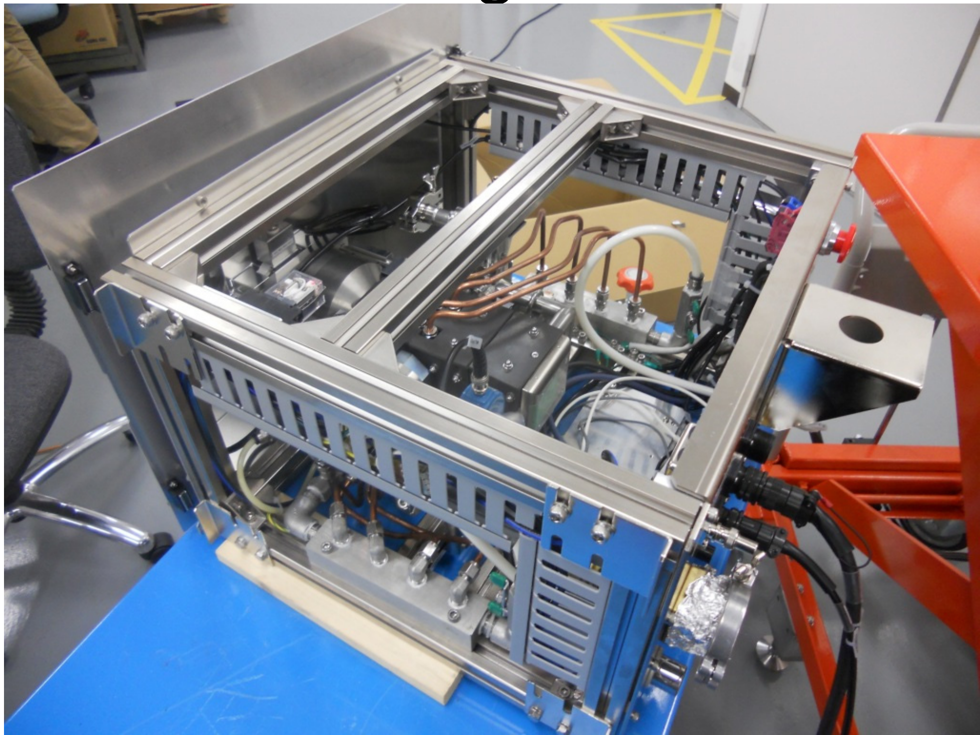
Compact 2450 MHz
CW Linear Accelerator

1 MeV Accelerator for NDT



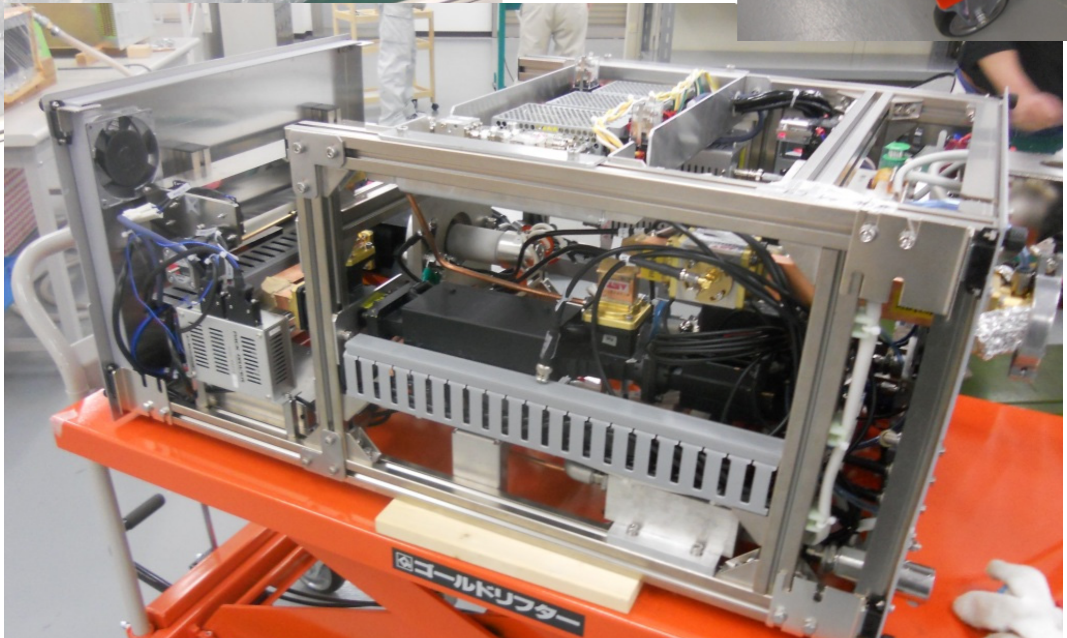
X-Band Standing Wave
Accelerator ~15 cm

Accelerator Head ~35Kg
including Collimator



4 and 6MeV Accelerator for NDT

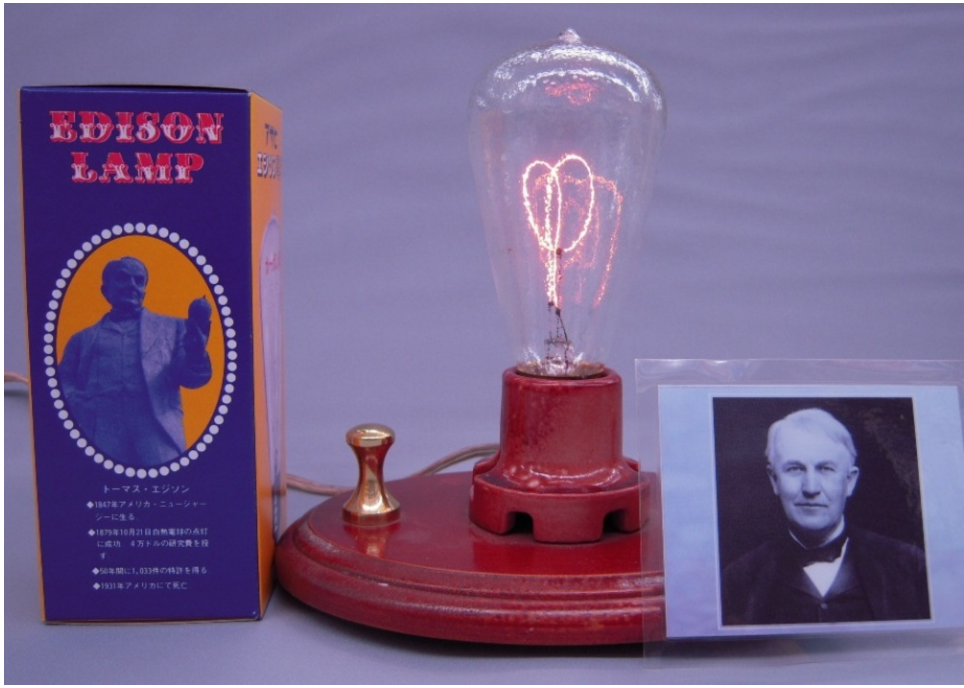
Suite Case Design



Technological Innovation

Innovation involves the whole process from opportunity identification, invention to development, prototyping, production, marketing, sales and support

1. Idea and Concept
2. Study Competitor, Cost, Market
3. IP and R and D
4. Business Plan
5. Fund Raise
6. Design and Manufacture
7. Testing and Verification
8. Packaging
9. Pricing and Sales
10. QA and QC
11. Support and Version Up



SUMMARY

1. Advances in accelerator technology have significantly contributed to the world healthcare. Electron linear accelerators are key contributors to the success of radiation therapy and NDT.

2. The medical community needs innovation in more effective treatment methods and technologies other than IMRT, stereotactic therapy, or interstitial radiation therapy.

Let's "Think Different"