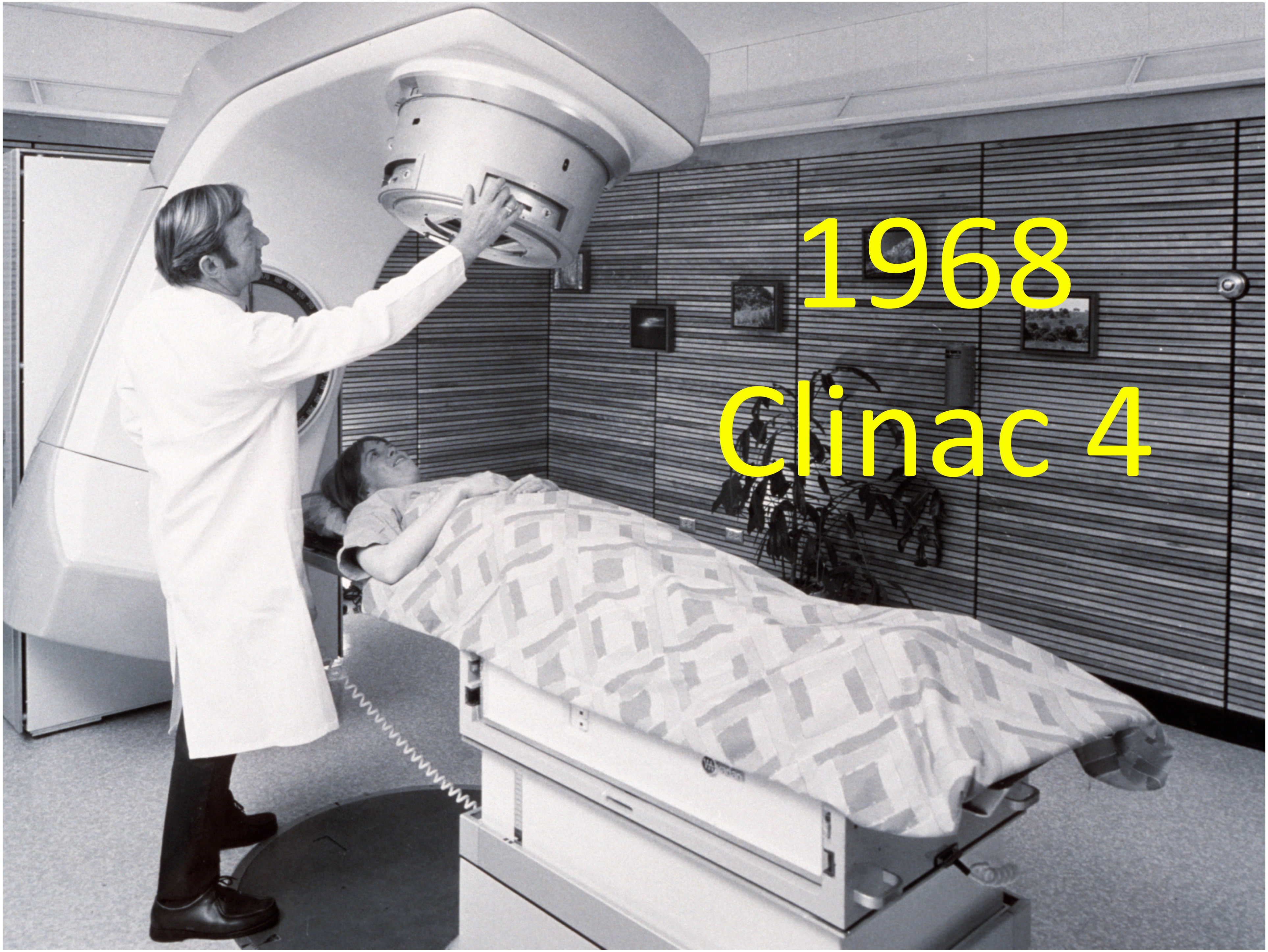
Opportunities Beyond the State of the Art in Electron Accelerator Systems

Dave Whittum

An introduction to the challenges for commercial electron accelerator systems and components, with an overview of design scalings, and discussion of possible research topics relevant to commercial applications in medicine, industry and security.

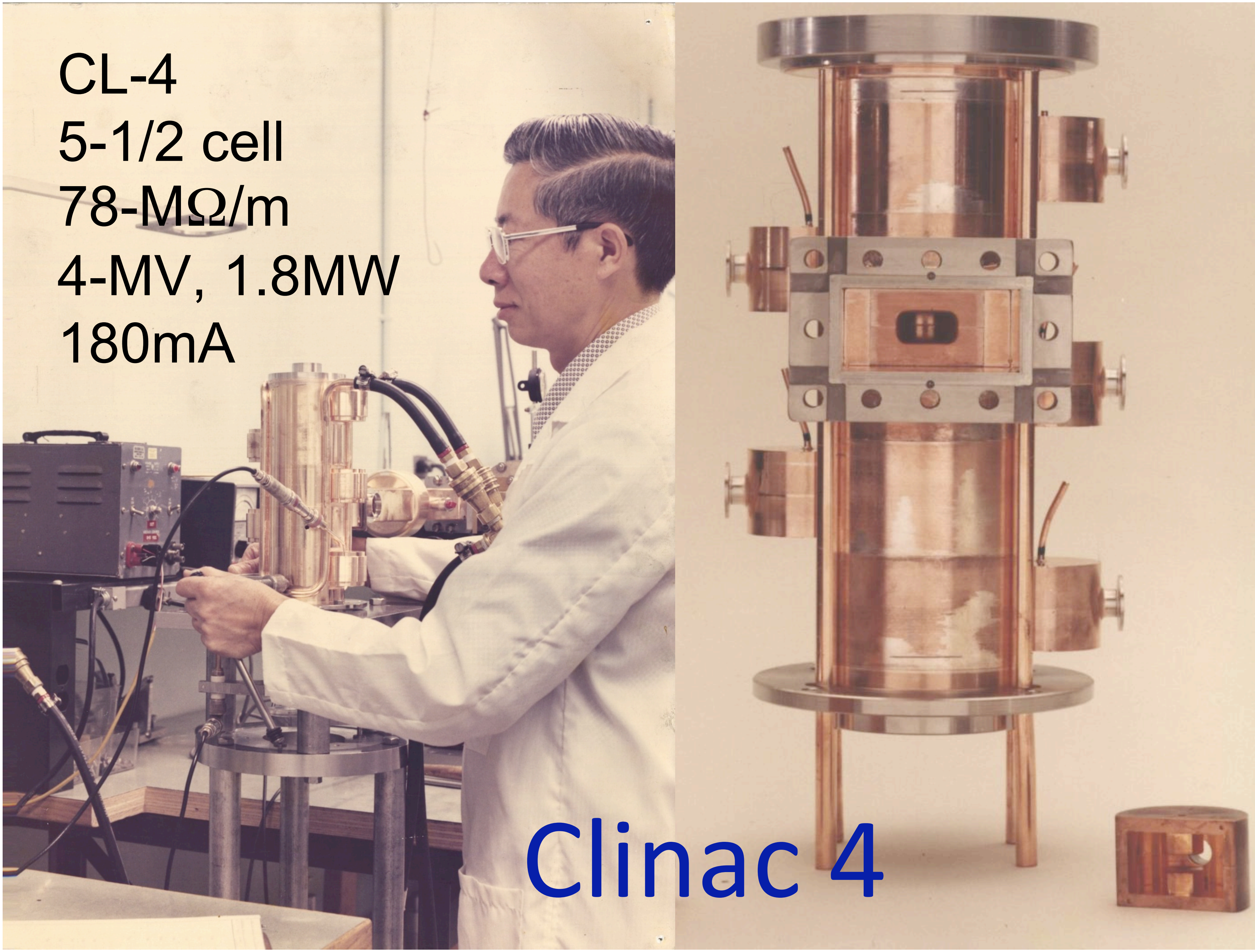
Fermilab

June 14, 2012 Curia II, Wilson Hall


1968
Clinac 4

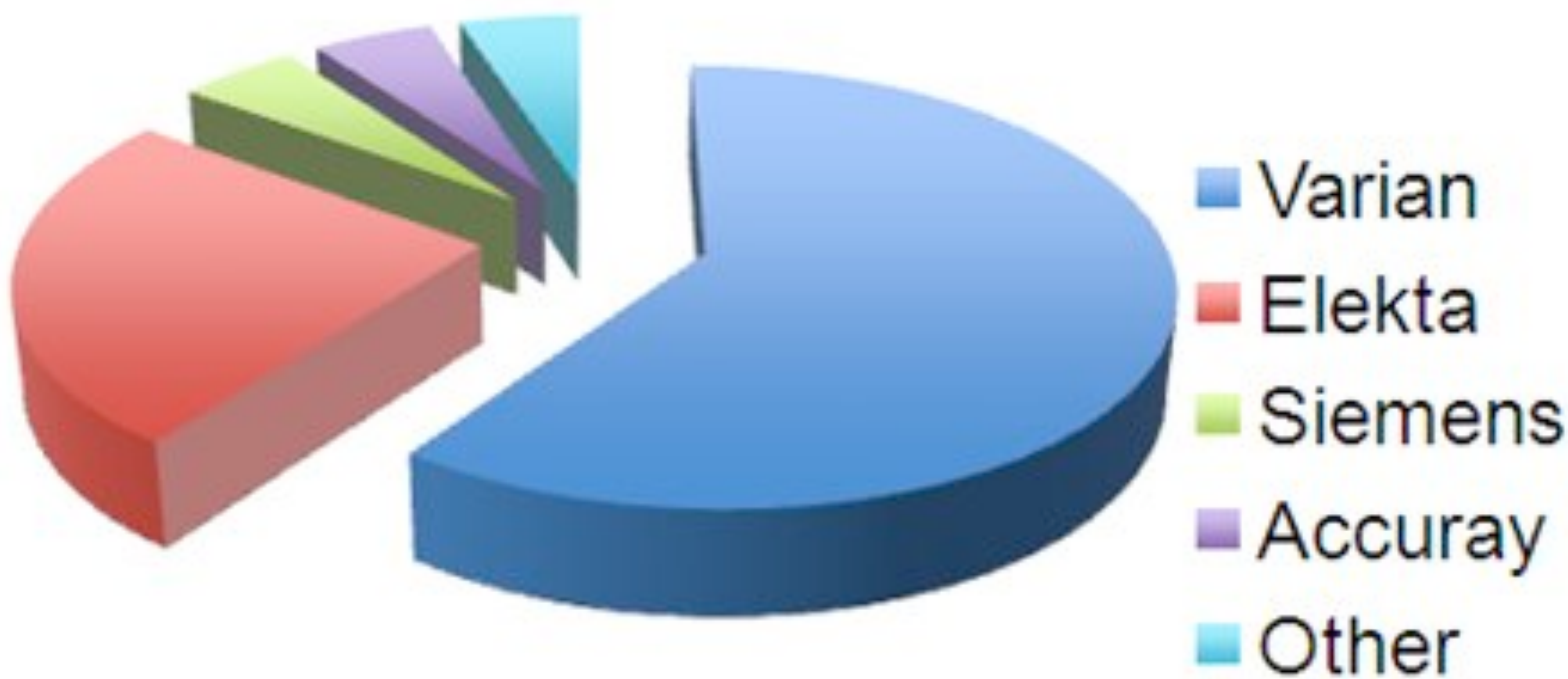
Clinac 4

CL-4
5-1/2 cell
78-MΩ/m
4-MV, 1.8MW
180mA

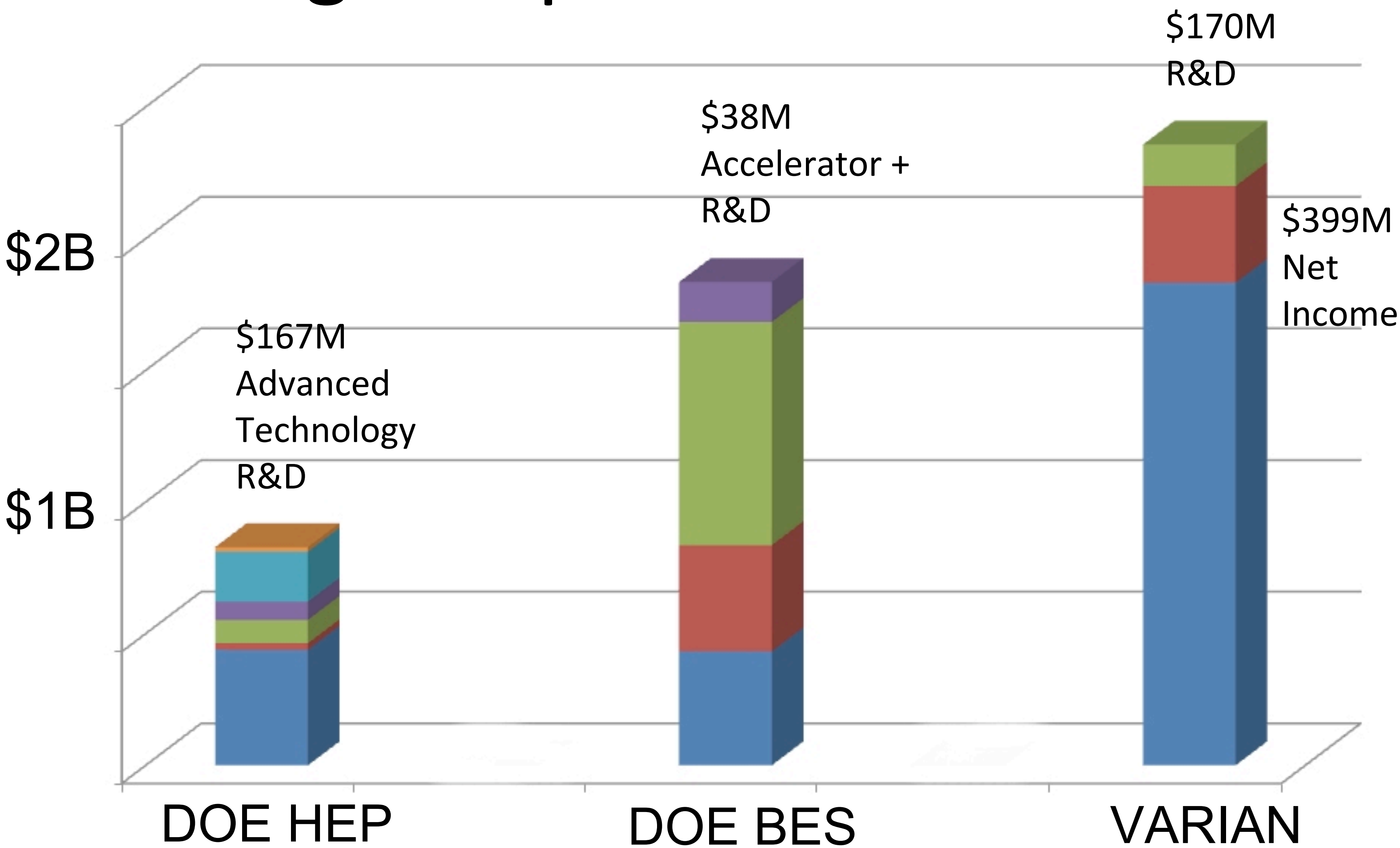


Business

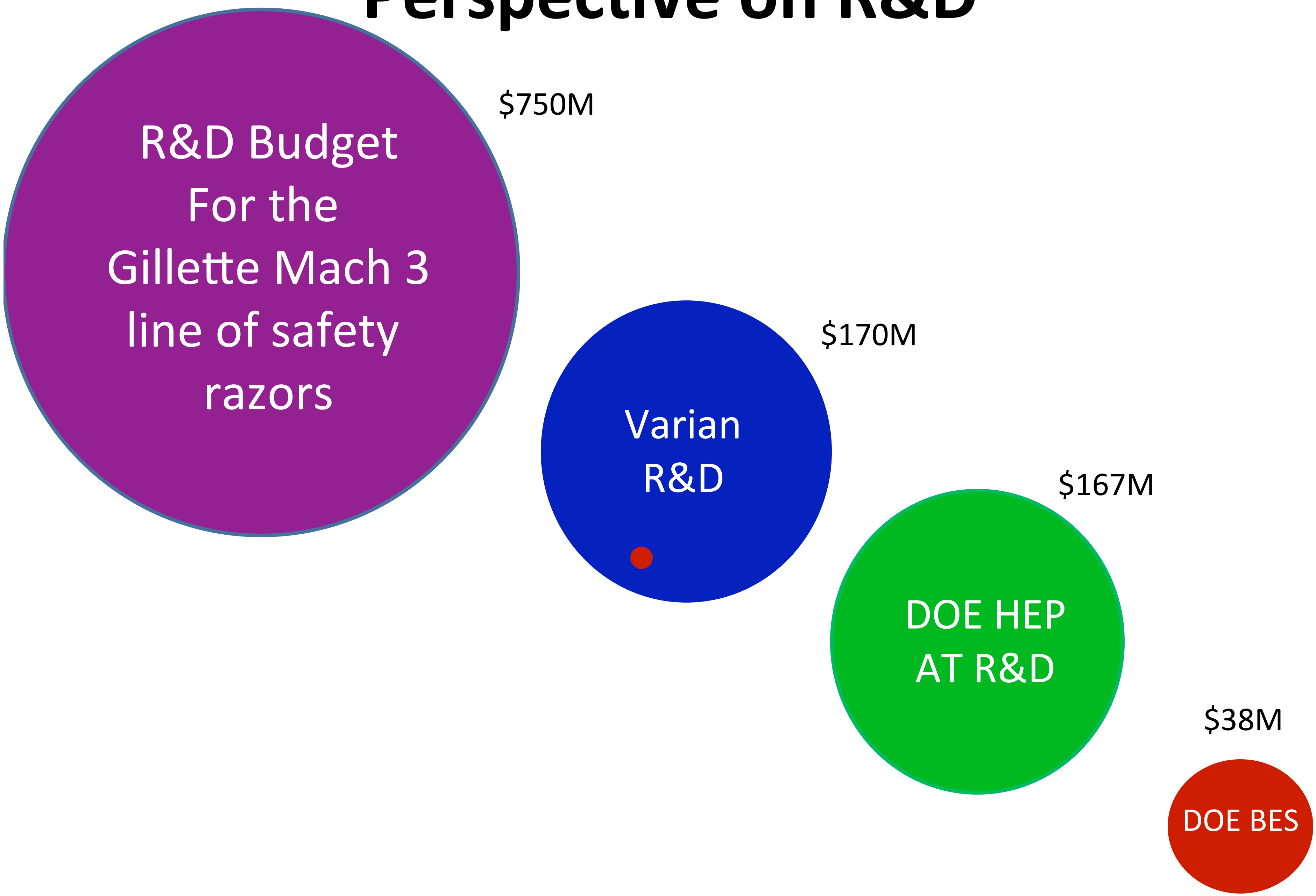
Annual Oncology Market: $4B



Funding Perspective



Perspective on R&D



National Lab for Razor Research?

Questions

What is the Purpose of a National Lab?

Why pursue Electron Linac R&D?

What Electron Linac R&D would be beneficial to commercial applications?

Resources

- Radiation Transport
  - GEANT, EGS, MCNP
  - Dosimetry, Radiation Safety, Victoreen
- Electromagnetics
  - Microwave Measurement, Network Analyzer
  - CST Microwave Studio, HFSS
- Mechanical Engineering
  - Thermal - COSMOS, COMSOL
  - Static, Dynamic Loads - Finite Element Models
  - Design for manufacture, Solidworks, ProE
  - Inspection, CMM
- Materials Science
  - AL995, 304L SST, OFE CU
  - Step braze, TIG weld
- …

What R&D would be beneficial?

- Same performance, lower cost

- Better performance, same cost

Understand the customer needs.

What is the value to the customer?

What is the total cost of ownership?

profit < value - cost

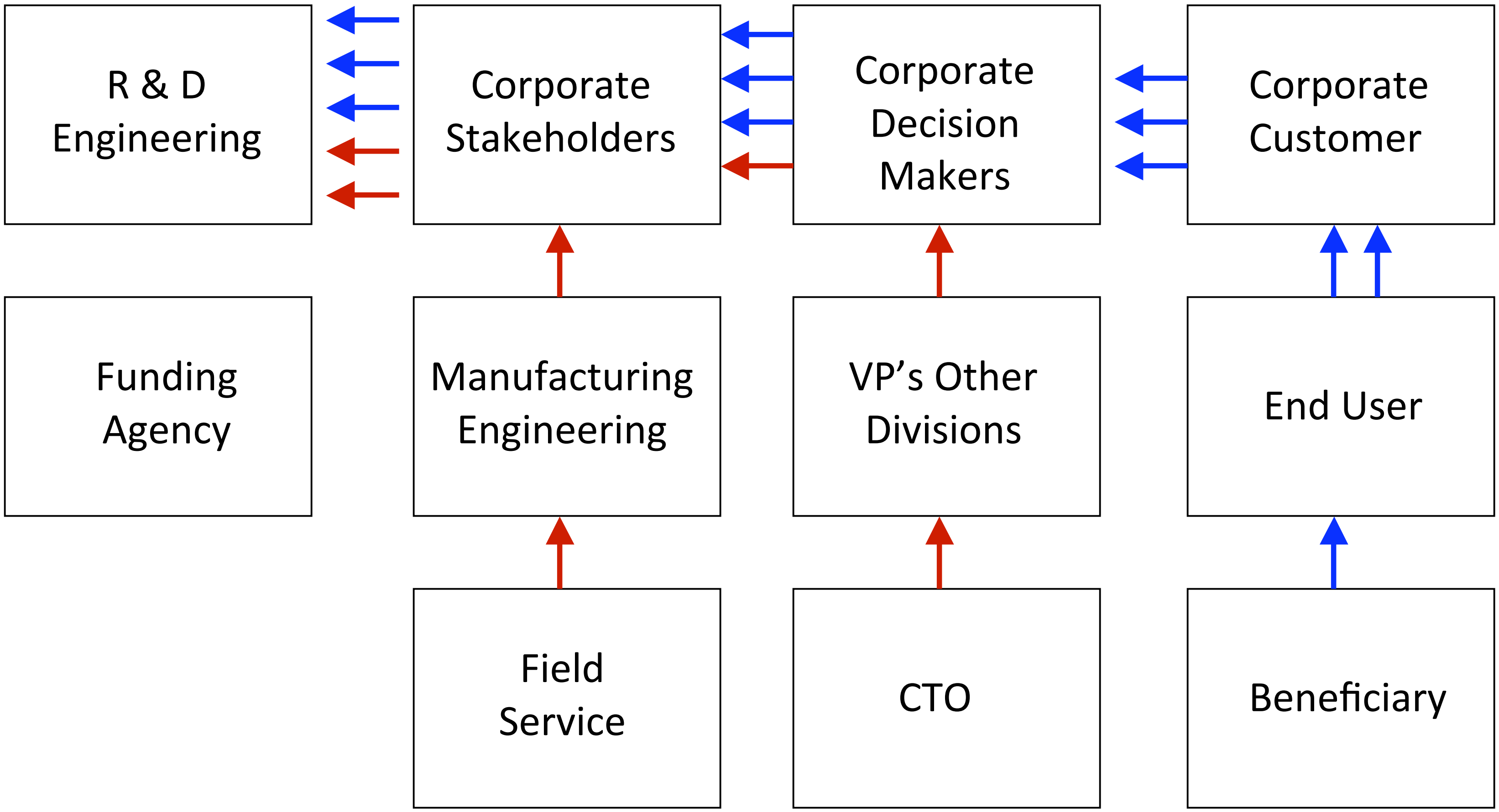
Example: Hesco

Caltrans: (emphasis added)

hescoxray.com

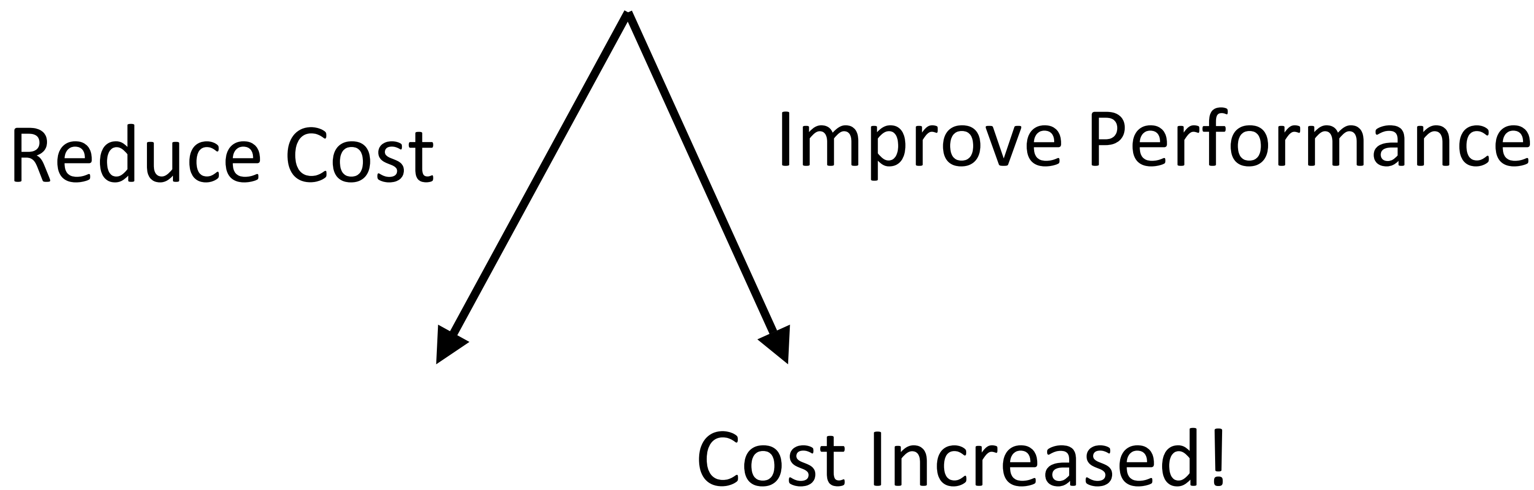
"In 1988, failures of vertical suspender cables on the Guy West Pedestrian Overcrossing Bridge in Sacramento prompted a major research effort to determine the condition of other bridges of similar design. The first application was on the San Francisco Bay Bridge between San Francisco and Oakland…The failures in the Guy West Bridge had occurred inside the socket by which the cable attaches to the bridge. <u>Isotope radiography was acceptable for examination of these smaller cables but could not image the large cables and sockets on the Bay Bridge.</u> Tests of the Bay Bridge sockets using a portable linear accelerator gave clear radiographs of the acceptable condition of it's sockets as well as providing base line data for future comparisons."

Customer Need?



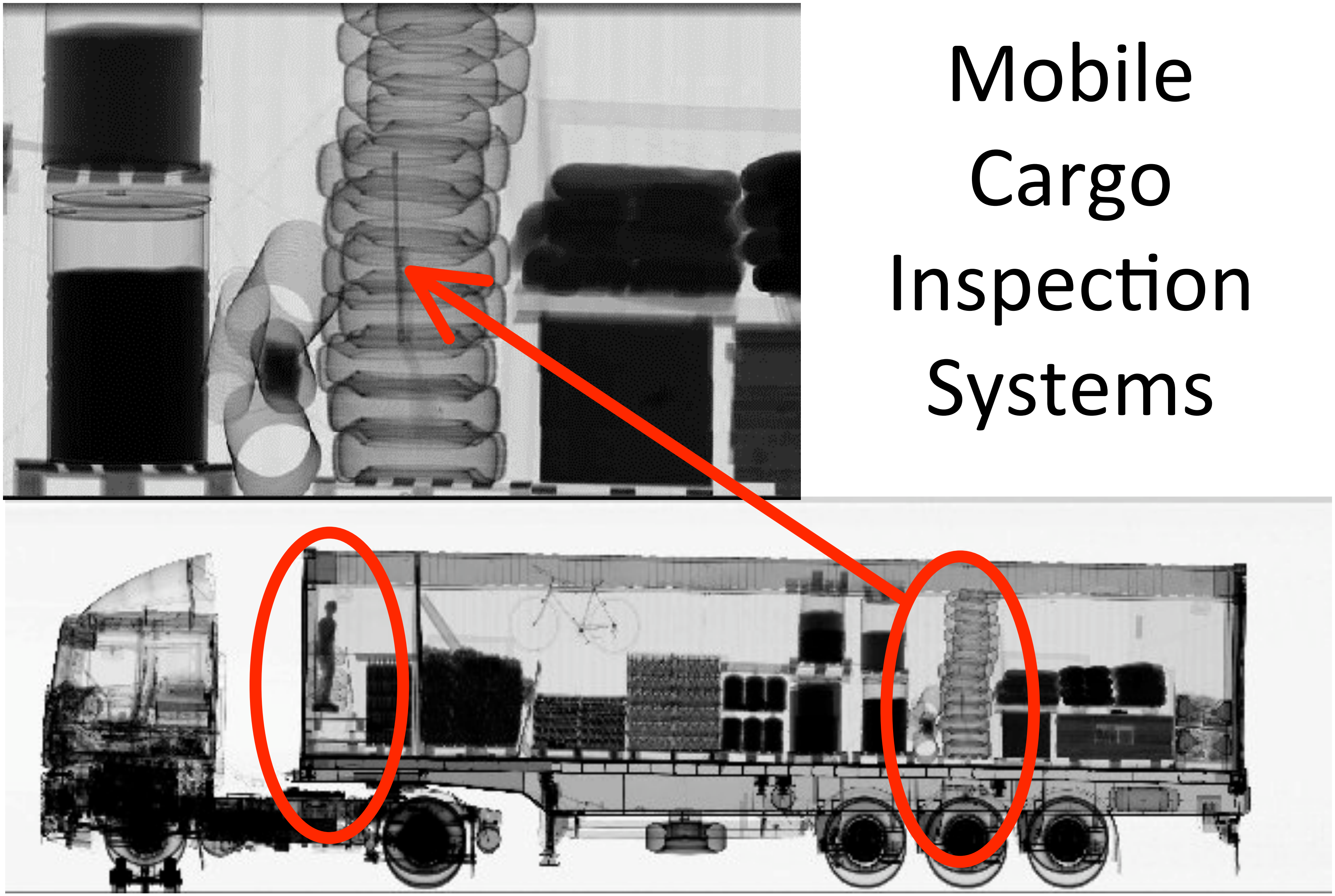
Decision Trees

What Problem Am I Trying To Solve?

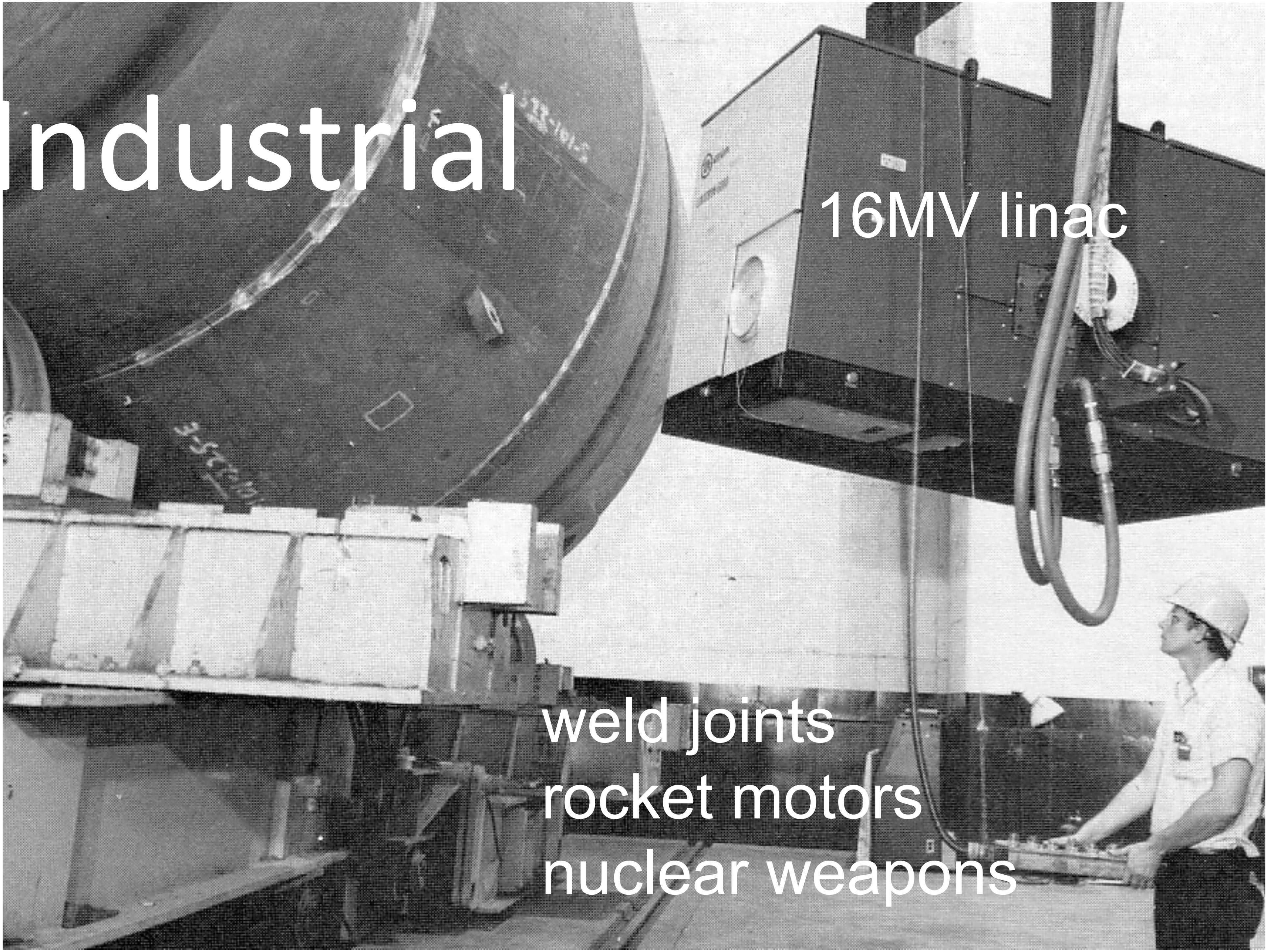


Security & Inspection

- Contraband, Dense Objects
- Border Crossings, Ports

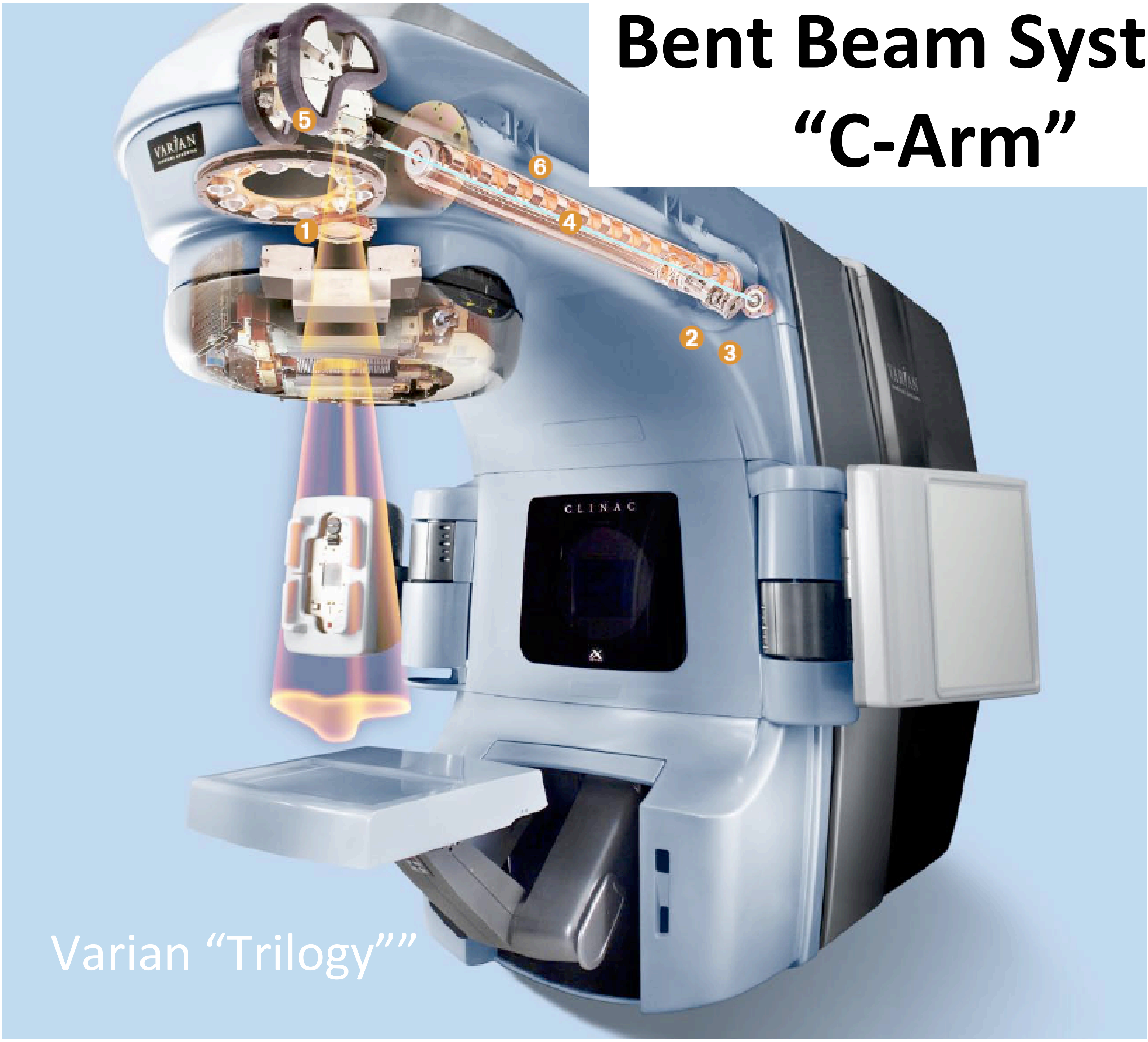


Mobile Cargo Inspection Systems

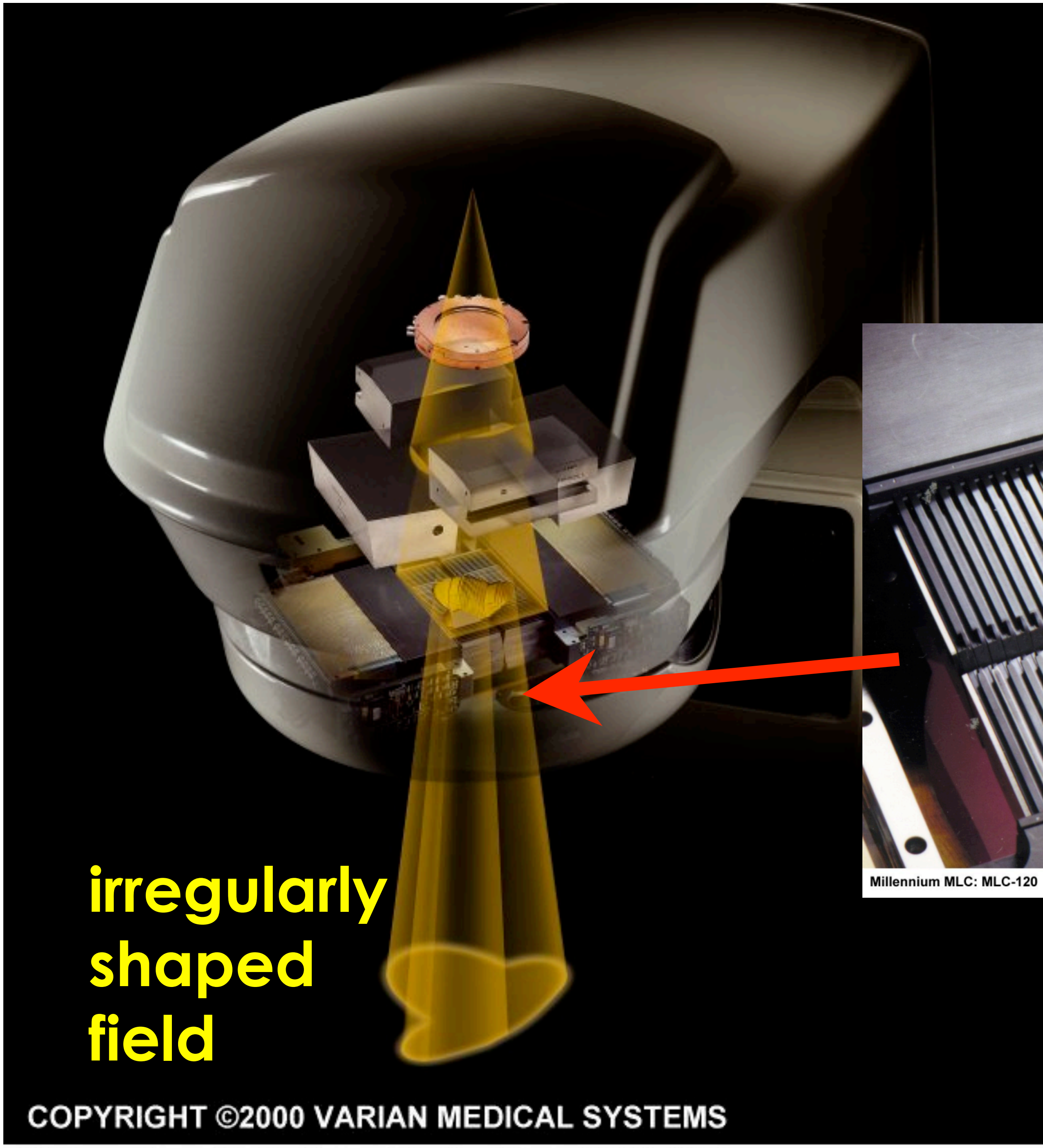

Industrial
16MV linac
weld joints
rocket motors
nuclear weapons


Medical Linear Accelerators
Elekta "Synergy"
delivering ionizing radiation to tumors,
sparing healthy tissue
ELEKTA

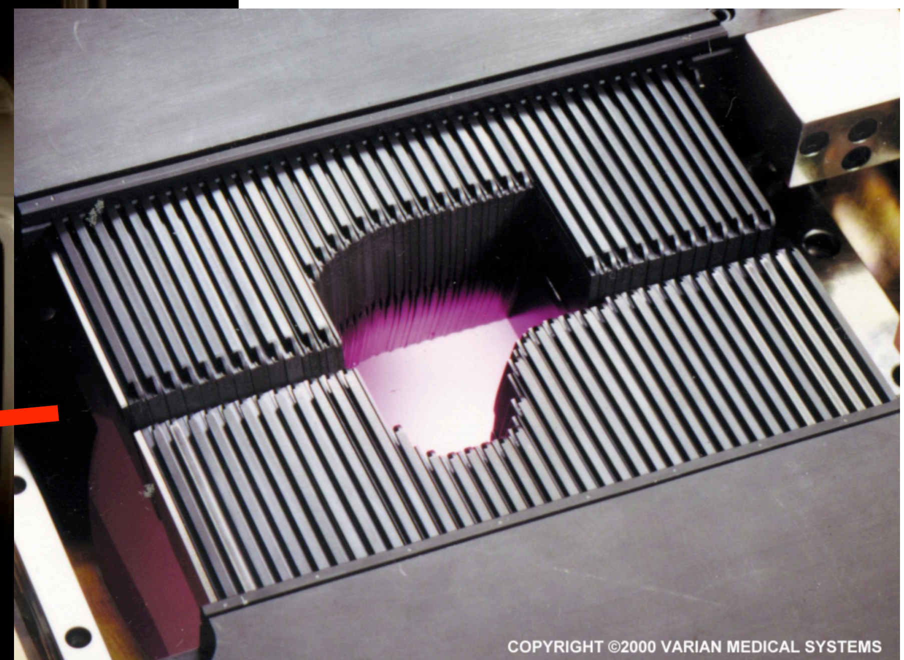
Bent Beam System
"C-Arm"



Multi-Leaf Collimator



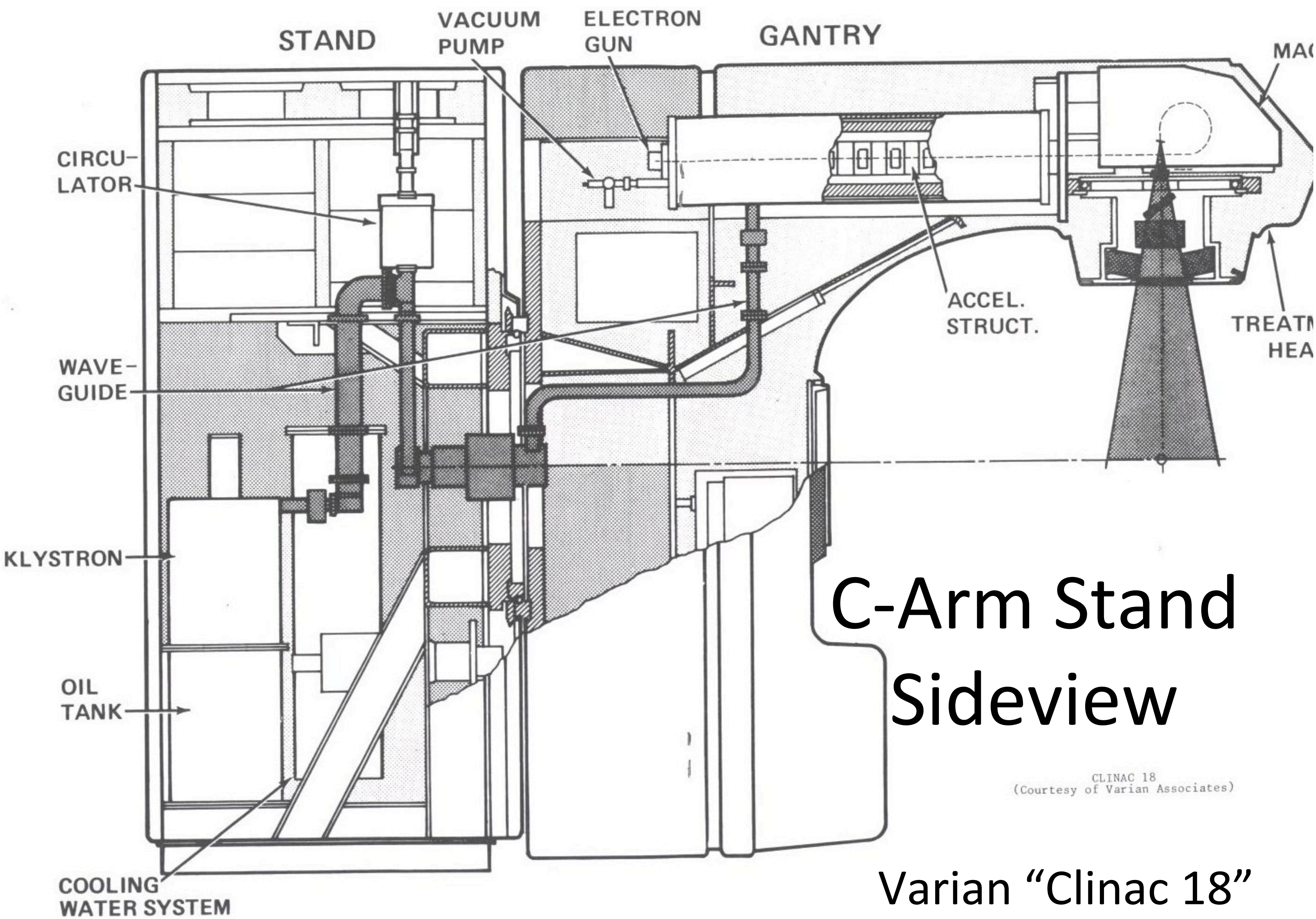
Millennium MLC: SomaVision™ and VARiS®



Millennium MLC: MLC-120

120 tungsten "leaves"

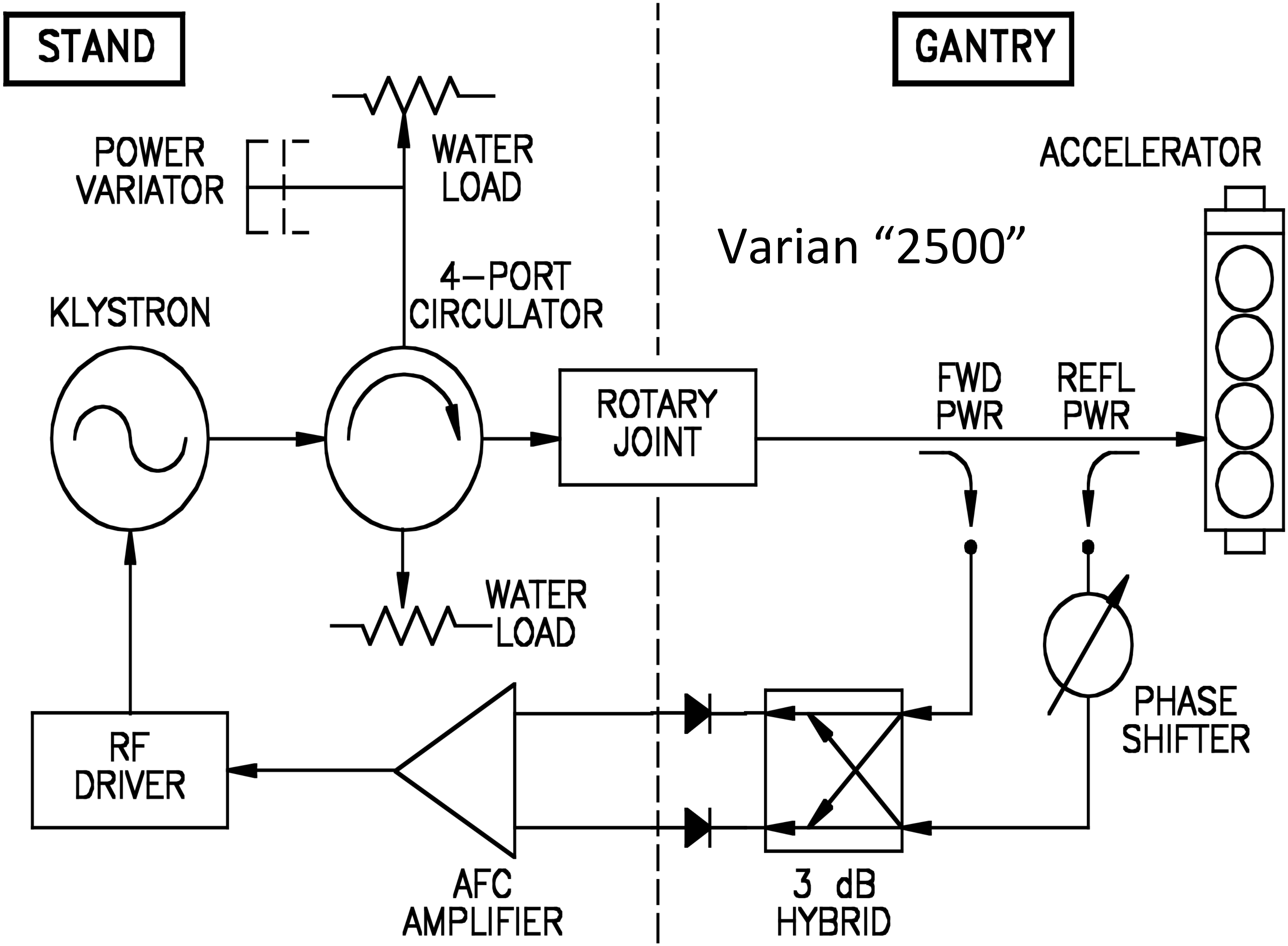
C-Arm Stand Sideview



CLINAC 18
(Courtesy of Varian Associates)

Varian “Clinac 18”

Linac RF System Schematic

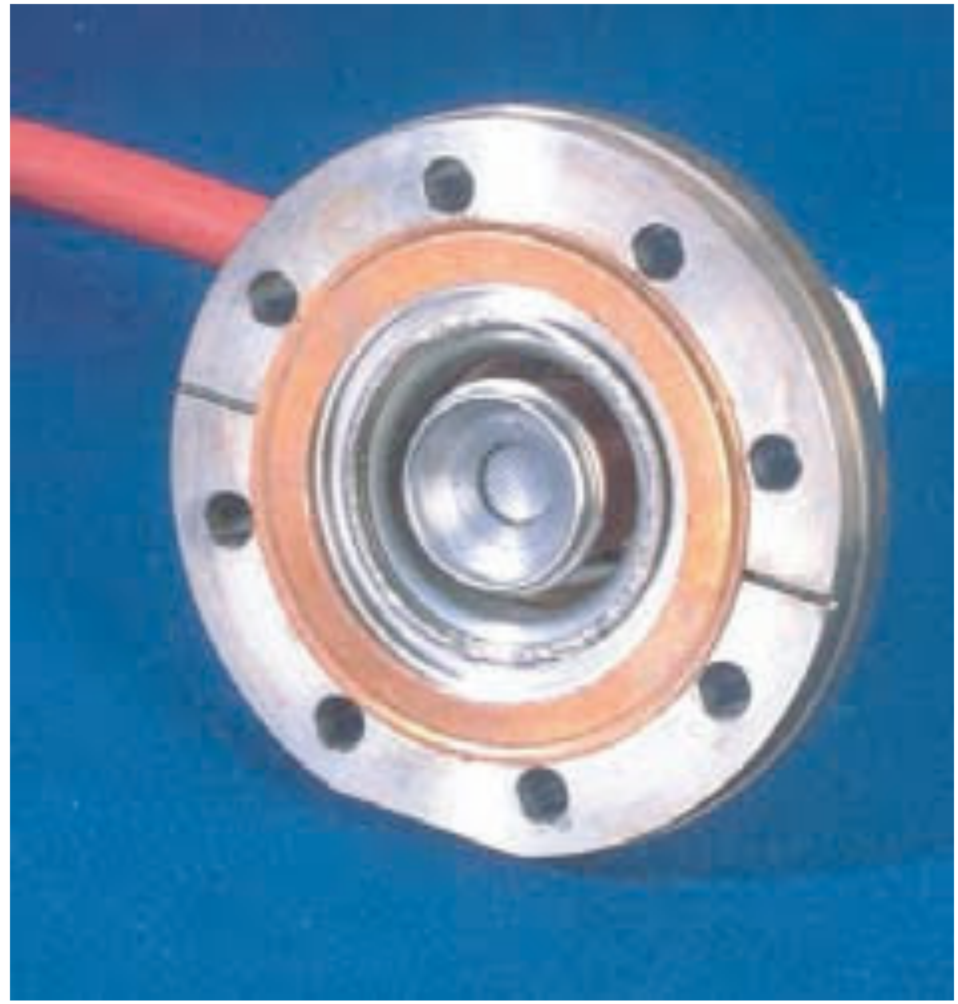


Reduce Cost of Goods

$\$10^4$	$\$10^5$	$\$10^6$
Gun	Modulator	Facility
Window	Power Tube	
Circulator	Accelerator	
Rotary Joint	Imaging System	
Water Load	Collimation	
Gun Supply	Solenoid	
	Bend Magnet	

Example:Triode Gun

- Enables DC HV supply
- Modulating voltage is a low 200V
- Adds a bit of cost to the gun..
- Still need pulsed HV for tube and solenoid for beam optics.
- Ideal would be a gridded gun, such that beam optics is independent of modulating voltage…



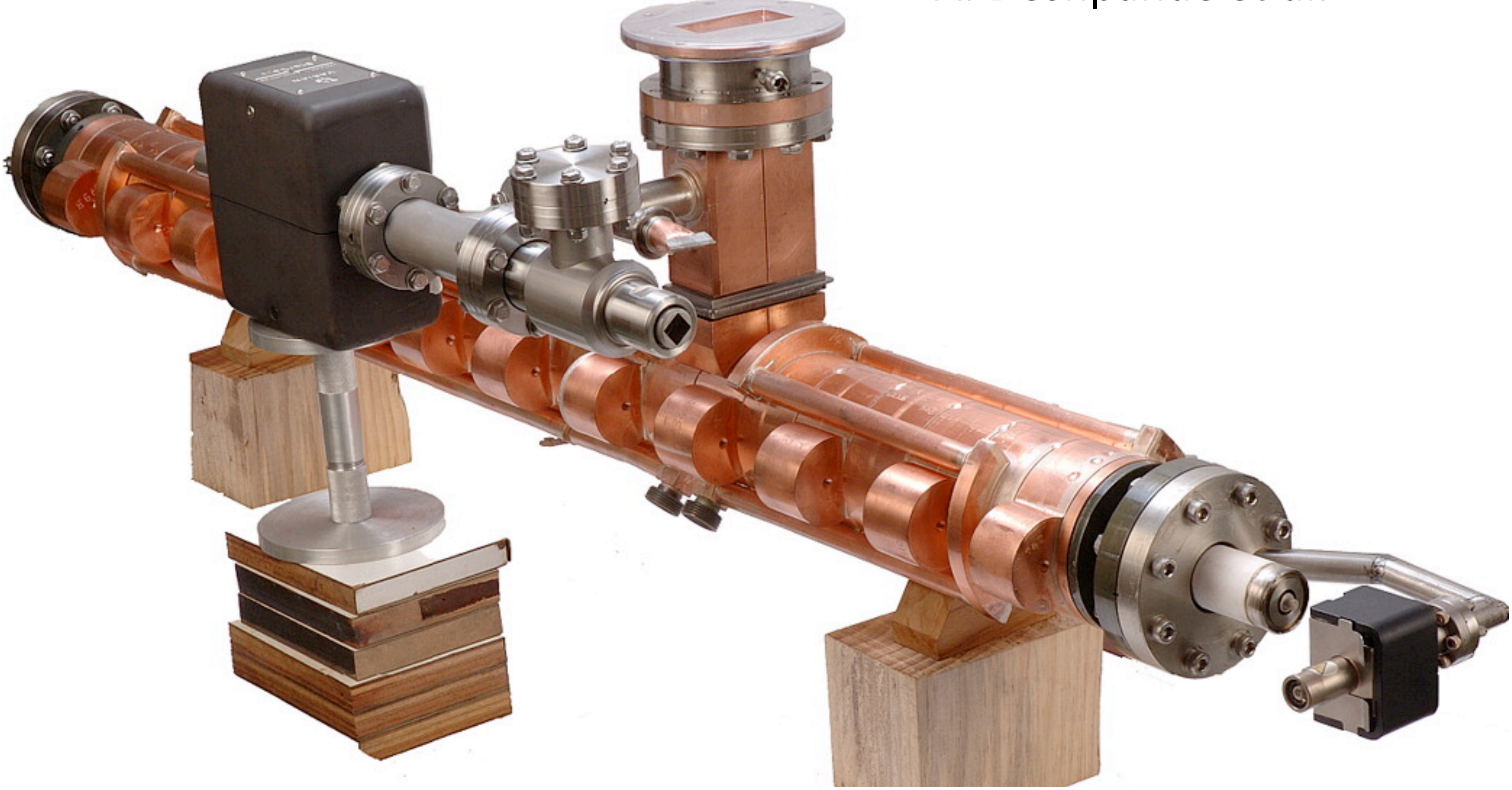
Improved Gun Could Lower System Cost

$\$10^4$	$\$10^5$	$\$10^6$
Gun	Modulator	Facility
Window	Power Tube	
Circulator	Accelerator	
Rotary Joint	Imaging System	
Water Load	Collimation	
Gun Supply	Solenoid	
	Bend Magnet	

Lowers Weight

High Energy Linac

A. Deshpande *et al.*



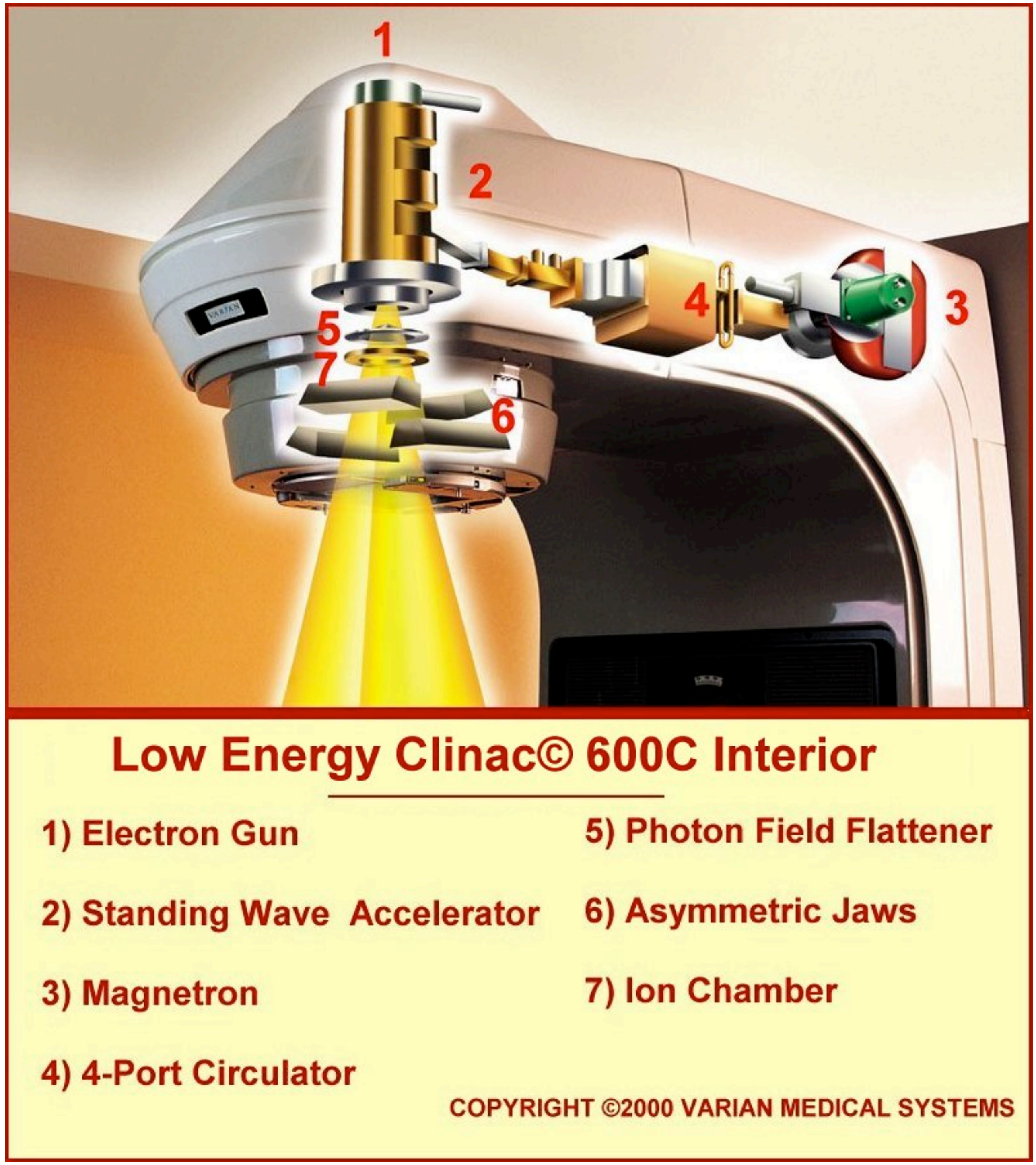
Cavities

Deshpande et al.

Shorten Production Cycle Time

Machine, Braze, Tune
Cold Test - Tune, Beadpull
Weld, Bolt
Bake
Solenoid - Fieldplot, Coil Adjustment
Gun Process
RF Process
Final Test

C-Arm Gantry, Straight-Ahead

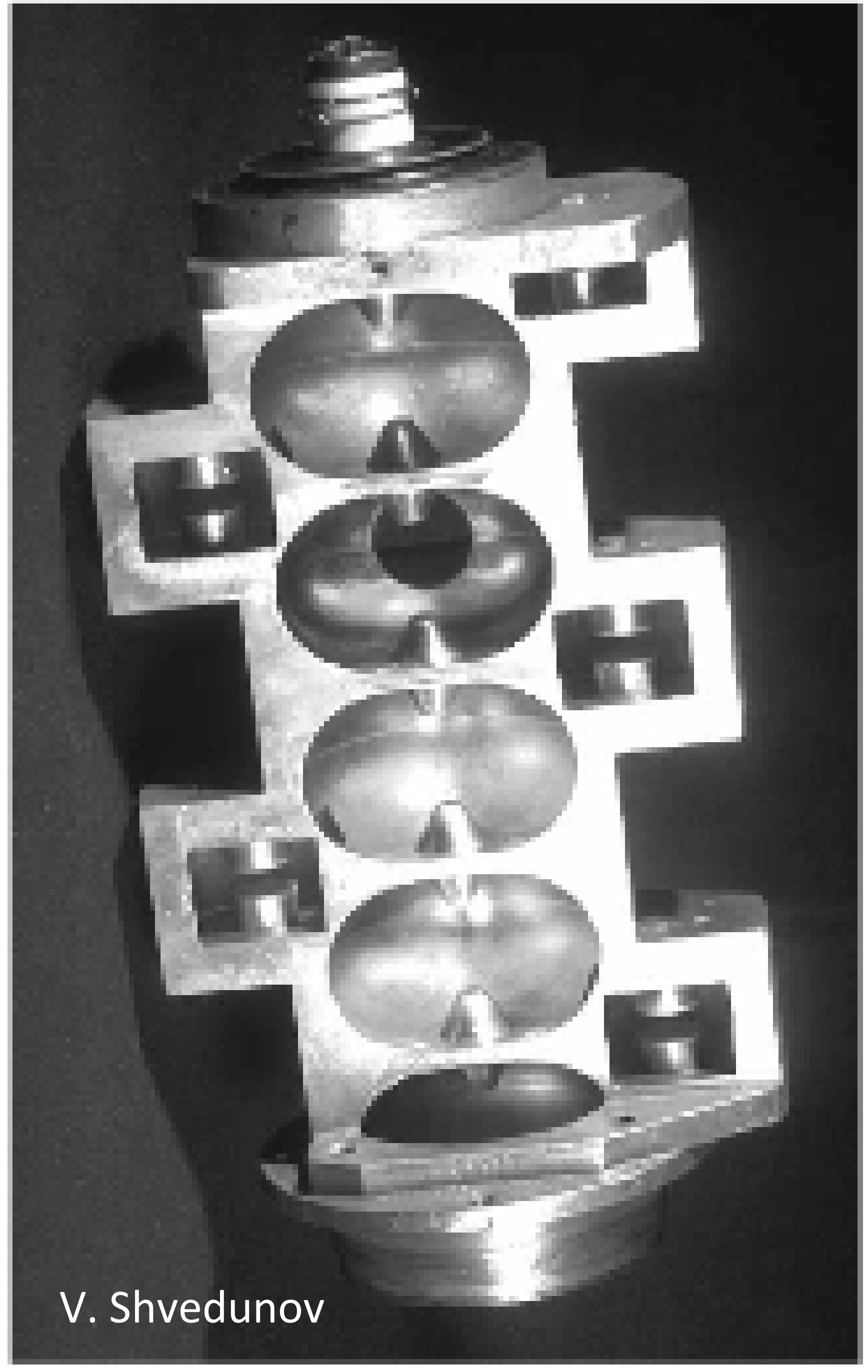


Straight-Ahead Linac

diode gun

integral target

baked, sealed



Magnetron

The data should be read in conjunction with the Magnetron Preamble and with British Standard BS9030 : 1971.

ABRIDGED DATA

Mechanically tuned pulse magnetron intended primarily for linear accelerators.

Frequency range	2992 to 3001	MHz
Peak output power	3.1	MW
Magnet	electromagnet MG6053	
Output	to no. 10 waveguide (72.140 x 34.04 mm internal)	
Isolator	the use of an isolator is recommended, see note 7	

Mechanical

Overall dimensions	see outline
Net weight	7.3 kg approx
Tuner revolutions to cover frequency range (see note 2)	4 approx
Method of mounting	see note 3
Mounting position (see note 4)	any

Cooling

The magnetron is water cooled and has an integral water jacket. The recommended water flow is 5 litres per minute or more; a pressure of approximately 1.25 kg/cm^2 will be necessary to give this rate of flow. The outlet water

Manufacturability

Relax tolerances
Fewer Braze Runs
No Au alloy
Fewer Unique Parts
Simpler Stack for Braze
Outsource w/o Loss of IP

Shorten Cycle Time
Automation
Reduce Inspection

Performance Improvement

Target – Yield, Limits

Energy Switch -Slow,Fast,Method

Accelerator - Footprint

Multileaf Collimator - Speed

Imaging –kV, MV, method

Modulator – PRF, Pulse Width, Footprint

Gun Supply – Diode vs Triode

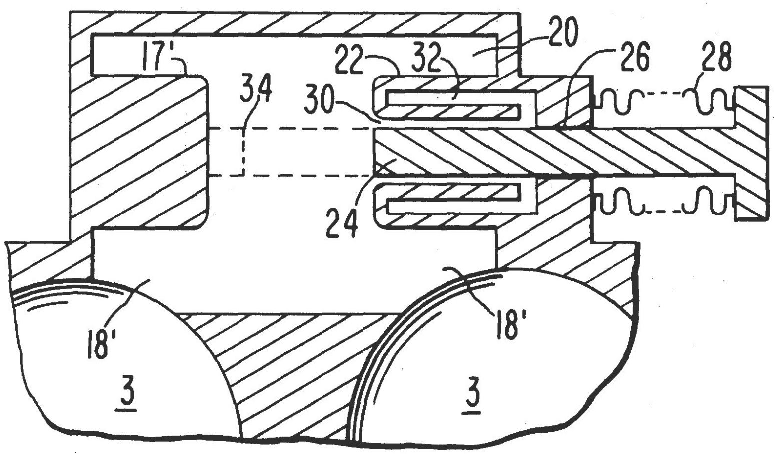
Power Tube – Peak, Average Power

Platform … New Applications, New Customers

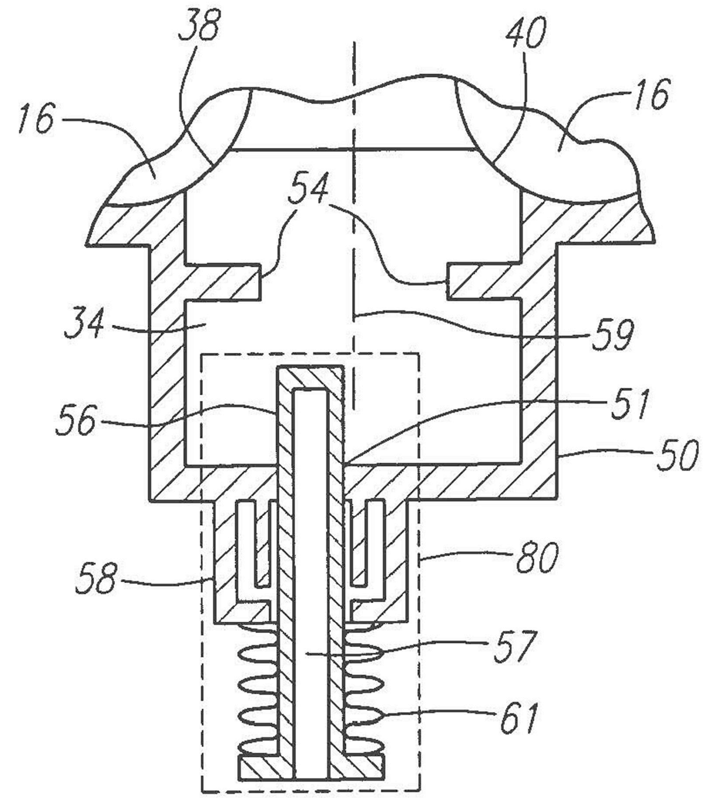
Methods of Changing Energy

Beam Loading (RF Power, Gun I, Gun V)
Energy Switch
Two Section Linac

Energy Switches



The Tanabe-Vaguine switch from US Patent No. 4,286,192.

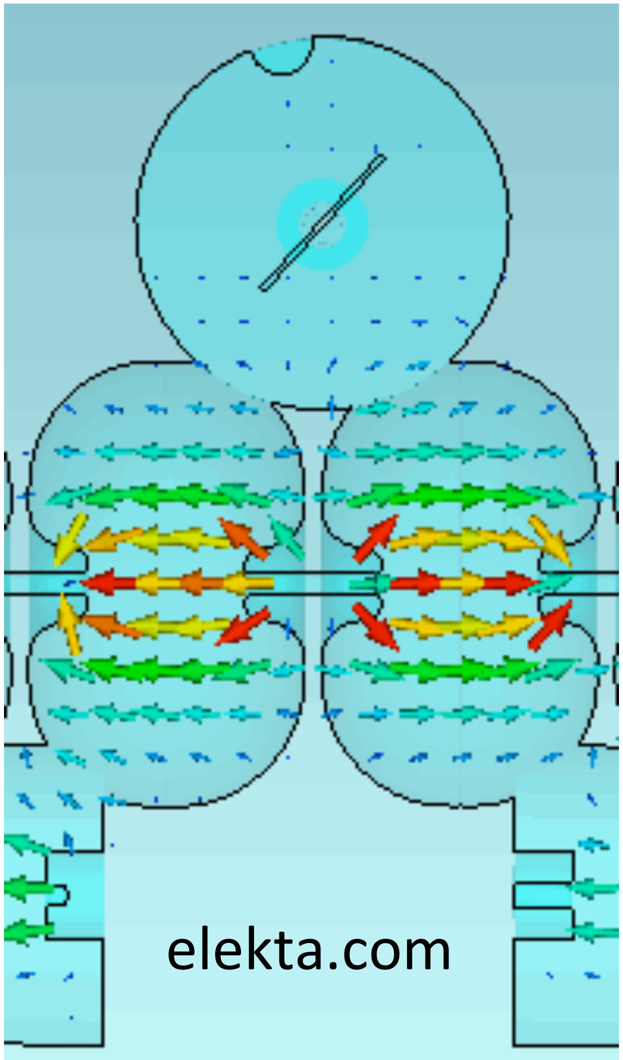


The field-step energy switch consists of a water-cooled, bellows-mounted sliding probe that perturbs a side-cavity resulting in a field step between the centerline cavities coupled through it.

Rotating mode coupling cavity

Courtesy John Allen, Elekta

- "Allows continuous variation of coupling between acceleration cells
- Variation of the coupling has minimal affect on frequency of system.
- Can invert the phase of the coupling to allow deceleration for low MV beams
- Principle of operation is based on the rotational degeneracy of the TE_{111} cylindrical mode."



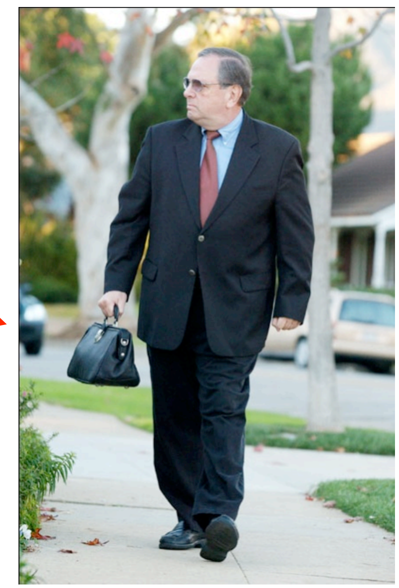
Magnet-Free
(straight ahead)

RF Focusing
Multi-Modality
Energy Definition
Electron Mode
Spot-Size
Gridded vs Diode, Gun Driver
Gradient Limits

Shorter Wavelength Accelerators

- Accuray - Cyberknife
- Intra-OP - Mobetron
- Tsinghua/Nuctech:
  - Active X-band development since 1991
  - Developed 2, 2.5 & 6MV accelerators for cargo
- Hitachi - C-Band Gimbal-mounted system
- University of Tokyo .95 MV X-Band
- W-Band, Laser…

smaller linacs are more versatile

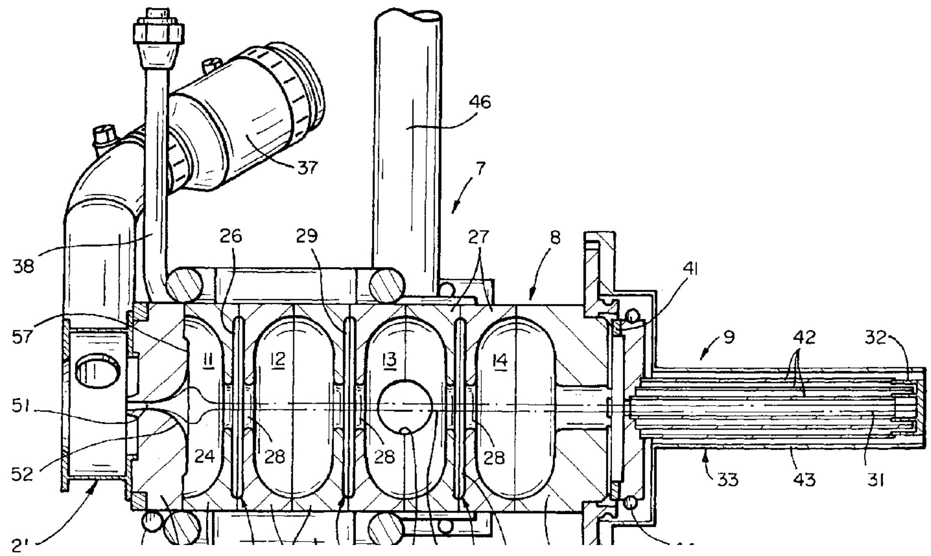


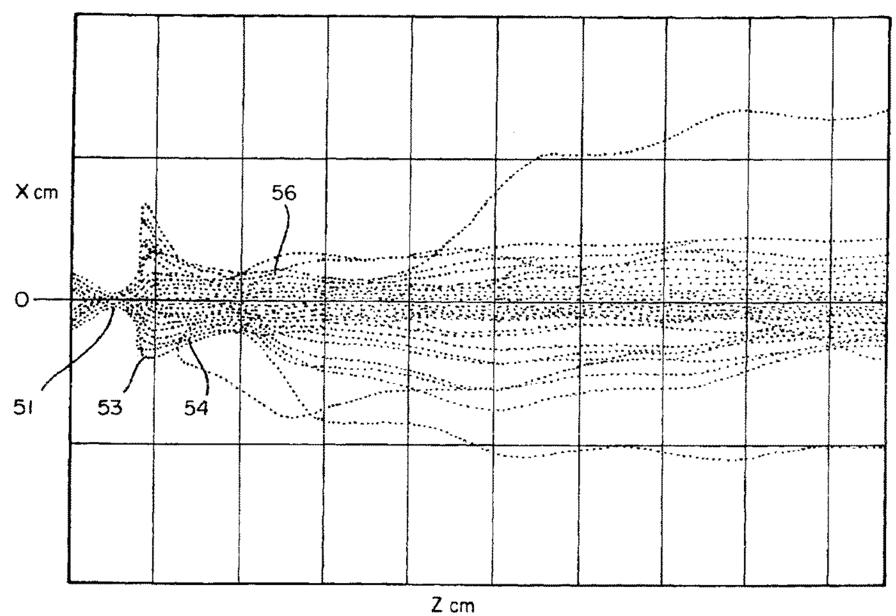
Shielding Requires Mass

Half-Value Layer (HVL)	2MV	6MV
Tungsten	0.9cm	1.2cm
Lead	1.3cm	1.7cm
Steel	2.0cm	3.1cm

design for low guide glow

still need shielding at 180deg





need shielding around the target

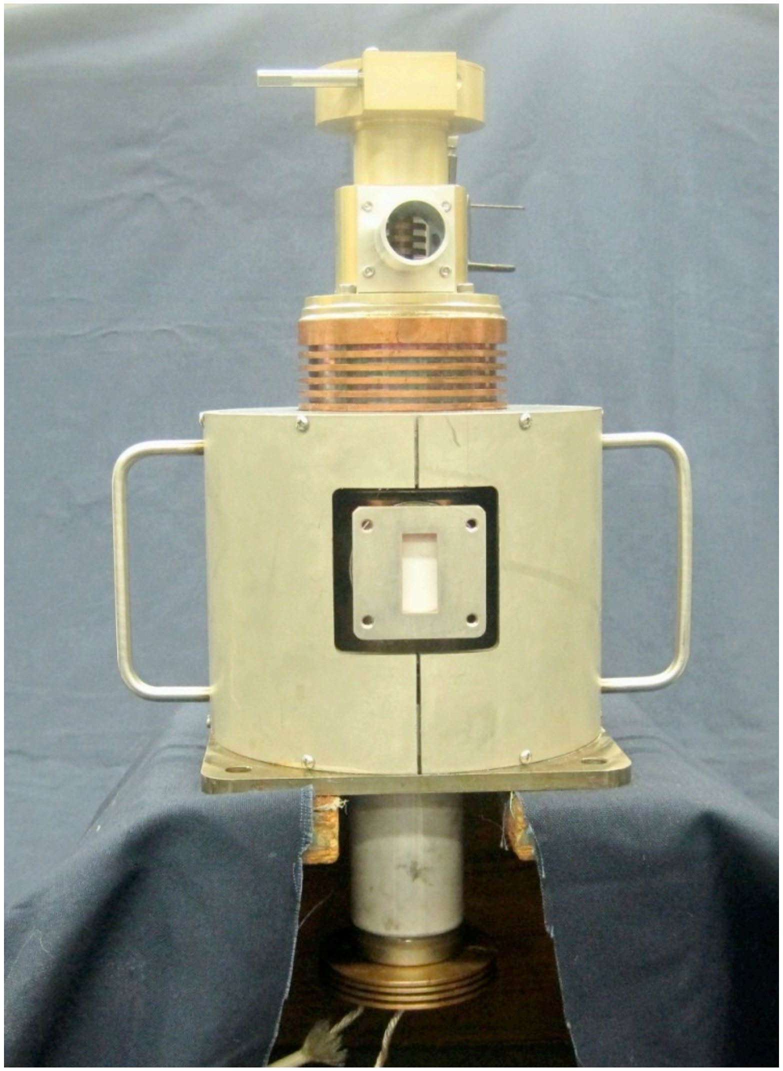
X-Band Magnetrons

Communications
& Power
Industries

VMX3045

Peak Power – 400 kW
Duty Cycle – 0.1 %

X-Band Magnetrons



Communications & Power Industries

VMX3074B

Peak Power – 400 to 1500 kW

Duty Cycle – 0.1 to 0.45 %

X-Band Magnetrons

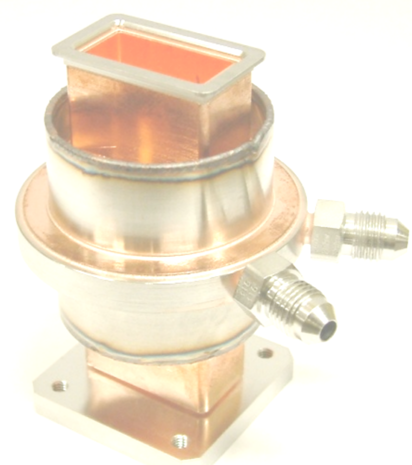
L-3 Cal Tube Lab

PM-450X Series	PM-1100X Series	PM-2000X Series
400 kW	1.8 MW	2.2 MW
1200 W ave	1600 W ave	600 W ave
35 – 38 kV	36 – 38 kV	34 – 38 kV
34 A	88 A	110 A
8 μs pulse length	4.5 μs pulse length	2.5 μs pulse length

X-Band Klystrons

L-3 Communications
Electron Devices Division

- Klystrons to 5 MW / 20 kW
- X-band RF drivers to 100 watts
- High power RF vacuum windows




Accuray
Cyberknife
ACCURAY

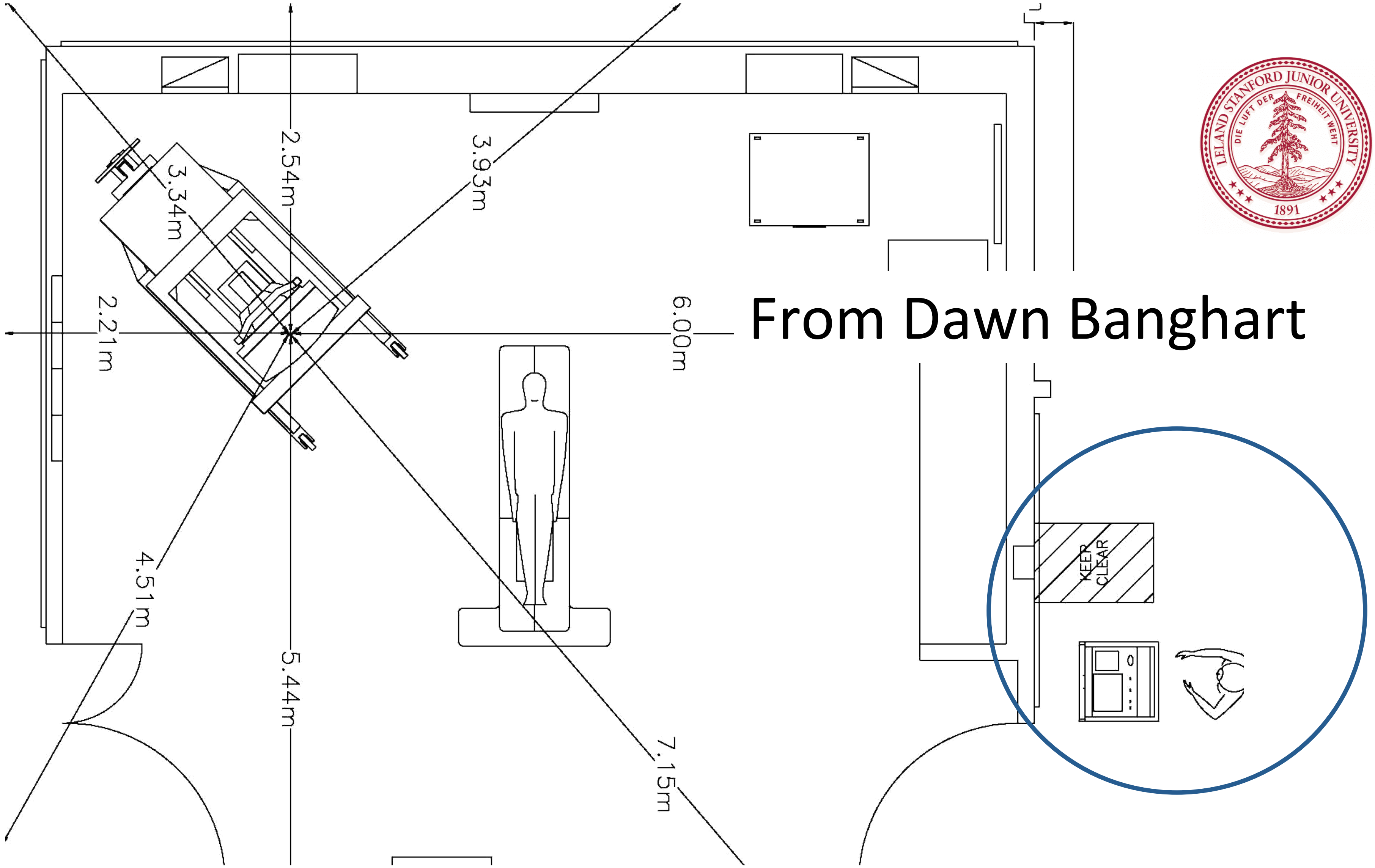
Mobetron

INTRAOP

Multi-Energy
800lbs
Self-Shielded

Great discussion of Mobetron from the Radiation Safety Perspective:

"Is More Pb the Answer in a Changing Medical Environment?", Dawn Banghart, CHP, Stanford University



From Dawn Banghart

Overhead view of OR room

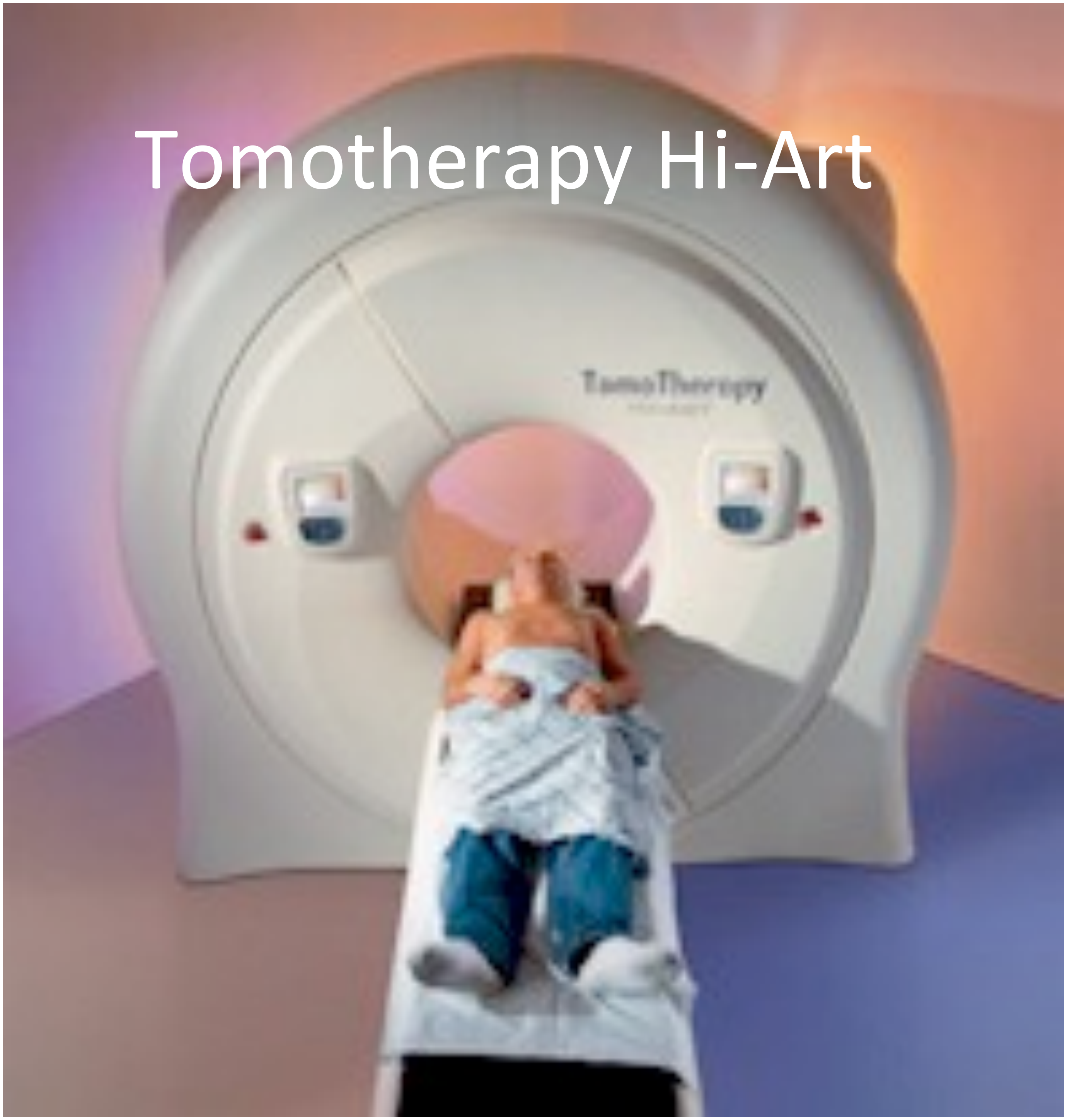
Target

Cyclic stress pulse-to-pulse
Cyclic stress per treatment
Water leaks
Ceramic leaks
External Target - Window

Platform for Delivery

C-arm
Tomotherapy
Accuray
Mobetron

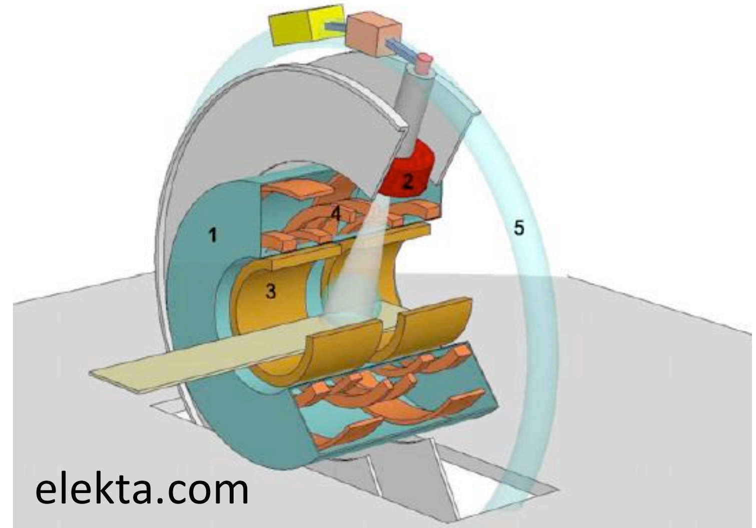
Tomotherapy Hi-Art



Combining a linac with an MRI

Courtesy John Allen, Elekta

- Treat the patient simultaneously with being imaged by a ‘conventional’ 1.5 T diagnostic MRI
- How to do this?
  - Mount the linac on a rotatable gantry around the MRI magnet
    - The radiation isocentre is at the centre of the MRI imaging volume
  - Modify the linac to make it compatible with the MRI
    - No magnetic material for most of the linac system
    - Minimise the effect of the residual magnetic field on the accelerator
    - Electrically screen the MRI from the linac system
  - Modify the MRI system to
    - Minimise material in the beam path and ensure it is homogeneous
    - Minimise magnetic field at the linac



What makes for successful innovations…

- Portal Vision *1995-*
- Millenium Multileaf Collimator *IMRT*
- Real Time Position Management *-2000-*
- Trilogy/On Board Imaging *IGRT*
- Rapid Arc
- Truebeam *-2010…*

power tube
gridded gun
achromat
accelerator design
energy switch

Stability
Output
Imaging
Motion Control

Manufacturability
Reliability
Serviceability
Performance
Cost

Focal spot motion of linear accelerators and its effect on portal image analysis

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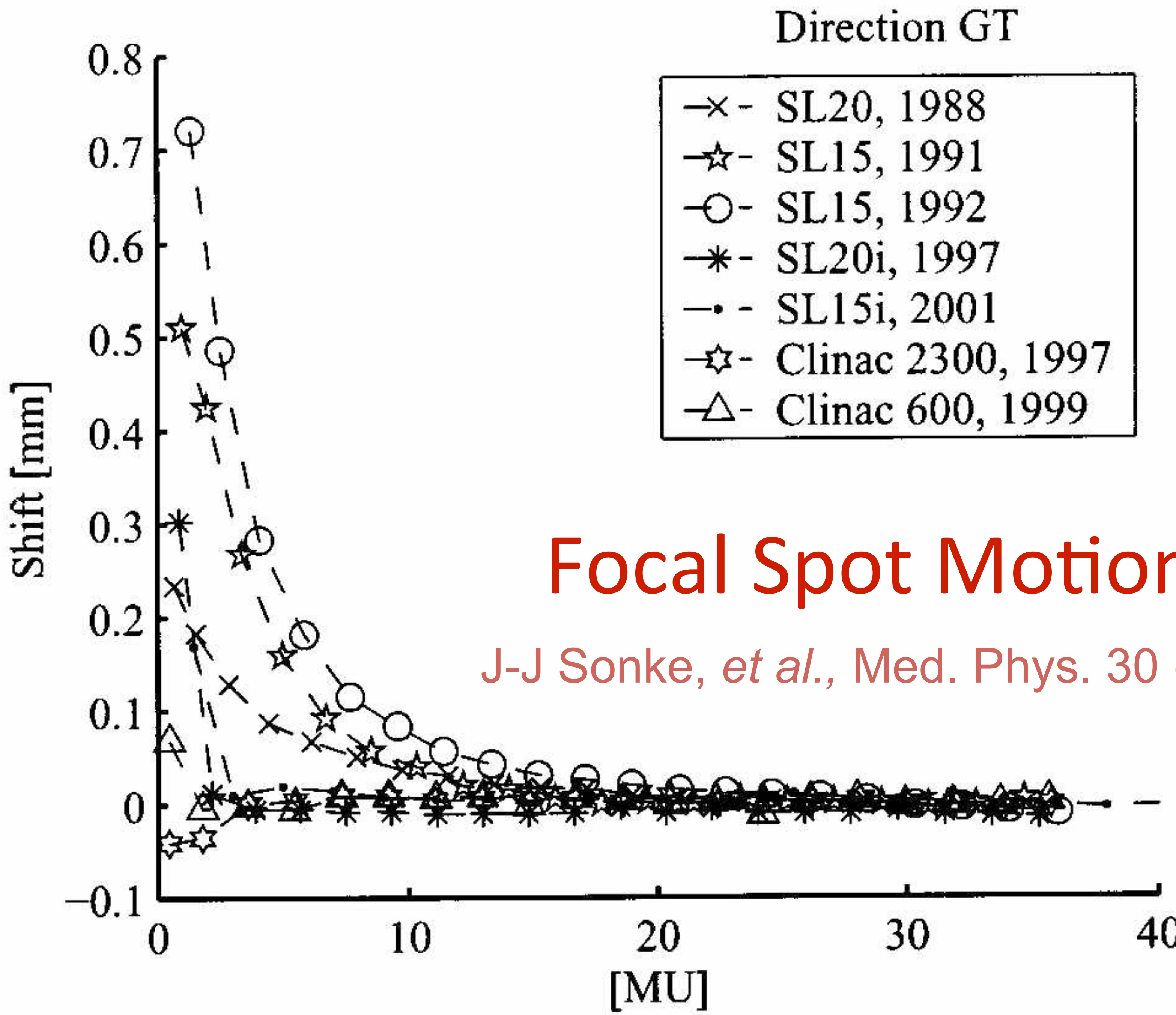
(Received 1 July 2002; accepted for publication 28 March 2003; published 23 May 2003)

The focal spot of a linear accelerator is often considered to have a fully stable position. In practice, however, the beam control loop of a linear accelerator needs to stabilize after the beam is turned on. As a result, some motion of the focal spot might occur during the start-up phase of irradiation. When acquiring portal images, this motion will affect the projected position of anatomy and field edges, especially when low exposures are used. In this paper, the motion of the focal spot and the effect of this motion on portal image analysis are quantified. A slightly tilted narrow slit phantom was placed at the isocenter of several linear accelerators and images were acquired (3.5 frames per second) by means of an amorphous silicon flat panel imager positioned ~0.7 m below the isocenter. The motion of the focal spot was determined by converting the tilted slit images to subpixel accurate line spread functions. The error in portal image analysis due to focal spot motion was estimated by a subtraction of the relative displacement of the projected slit from the relative displacement of the field edges. It was found that the motion of the focal spot depends on the control system and design of the accelerator. The shift of the focal spot at the start of irradiation ranges between 0.05–0.7 mm in the gun-target (GT) direction. In the left–right (AB) direction the shift is generally smaller. The resulting error in portal image analysis due to focal spot motion ranges between 0.05–1.1 mm for a dose corresponding to two monitor units (MUs). For 20 MUs, the effect of the focal spot motion reduces to 0.01–0.3 mm. The error in portal image analysis due

Focal Spot Motion



Focal Spot Motion

J-J Sonke, *et al.*, Med. Phys. 30 (6)

Linear accelerator output variations and their consequences for megavoltage imaging

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(Received 31 December 1997; accepted for publication 18 May 1998)

An experimental study of radiation output intensity fluctuations of a Philips SL25 linear accelerator is presented. Measurements are obtained using an electronic portal imaging device, and the consequences of the measured fluctuations for various different applications of megavoltage imaging including portal imaging, transit dosimetry and megavoltage computed tomography (MVCT) are discussed with examples. Fluctuations in output of ± 0.7% (1 SD) are seen on every radiation pulse after photon noise and uncertainties caused by the detection system have been accounted for. Large fluctuations are also seen during the initial beam stabilization period (15%), during normal accelerator operation after the beam has been on for more than 1 min (4.5%) and during arc therapy as a repeatable function of gantry angle (9%). Such output intensity fluctuations are shown to produce image artifacts in portal imaging devices with scanned detector readout and can also produce systematic errors in detector calibration that would lead to uncertainty in transit dose calculations. The propagation of these intensity fluctuations through MVCT image reconstruction is shown to produce ring artifacts in the reconstructed image. Sample portal and MVCT images are presented. All observed fluctuations in accelerator output are well within the manufacturer's specifications and do not affect the total dose delivered during normal treatment. Finally, megavoltage imaging is

Warmup

fluctuation

Suppression of dark current radiation in step-and-shoot intensity modulated radiation therapy by the initial pulse-forming network

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(Received 25 January 2002; accepted for publication 14 June 2002; published 8 August 2002)

Dark Current

The effect of the initial pulse forming network (IPFN) on the suppression of dark current is investigated for a Siemens Primus accelerator. The dark current produces a spurious radiation, which is referred to as dark current radiation (DCR) in this study. In the step-and-shoot delivery of an intensity modulated radiation therapy (IMRT), the DCR could be of some concern for whole body dose along with leakage radiation through collimator jaws or multileaf collimator. By adjusting the IPFN-to-PFN ratio to >0.8, the DCR can be measured with an ion chamber during the "PAUSE" state of the accelerator in the IMRT mode. For 15 MV x rays, the magnitude of the DCR is approximately equal to 0.7% of the dose at d_{max} for a 10×10 cm^2 field. The DCR has a similar central axis depth dose as a 15 MV beam as determined from a water phantom scan. When the IPFN-to-PFN ratio is lowered to <0.8, no DCR is detected. For low energy x rays (6 MV), no DCR is detected regardless of the IPFN-to-PFN ratio. Although the DCR is studied only for the Siemens Primus model accelerator, the same precaution applies to other models of modern accelerators from other vendors. Due to the large number of field segments used in a step-and-shoot IMRT, it is imperative therefore, that dark current evaluation be part of machine commissioning and annual calibration for high-energy photon beams. Should DCR be detected, the medical physicist should work with a service engineer to rectify the problem. In view of DCR and whole body dose, low-energy photon beams are advisable for IMRT. [DOI: 10.1118/1.1500403]

Challenges for Innovation

Cost of Goods
Protection of IP
Time to Market
Bureaucracy
Fear
Non-profit syndrome

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Nick Cortese.

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John Powers, Intra-Op
John Allen, Elekta
Peter Beasley, Siemens
Swapan Chattopadhyay, Cockroft Institute

References

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http://dx.doi.org/10.1016/j.nima.2010.02.023

V. Shvedunov, "Low Energy Electron Accelerators Applications"
http://icc.ub.edu/congress/ESP-RUS2011/talks.php


Questions