UMC Utrecht

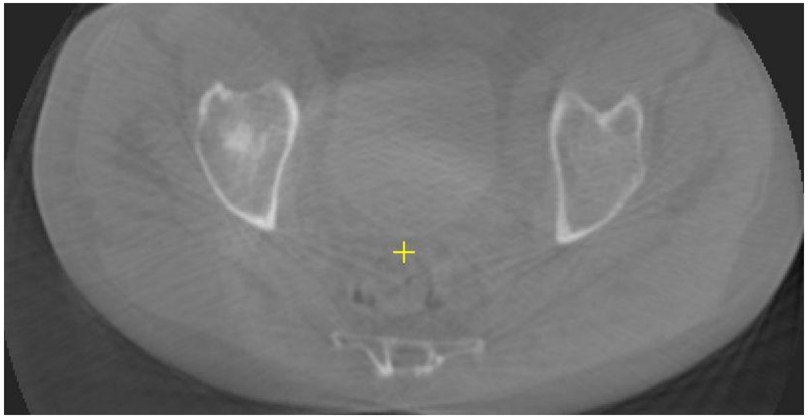
Past, Present and Future: MRI-guided Radiotherapy from 2005-2025

Jan Lagendijk, Bas Raaymakers, Marco van Vulpen

The goal of MRI guided Radiotherapy

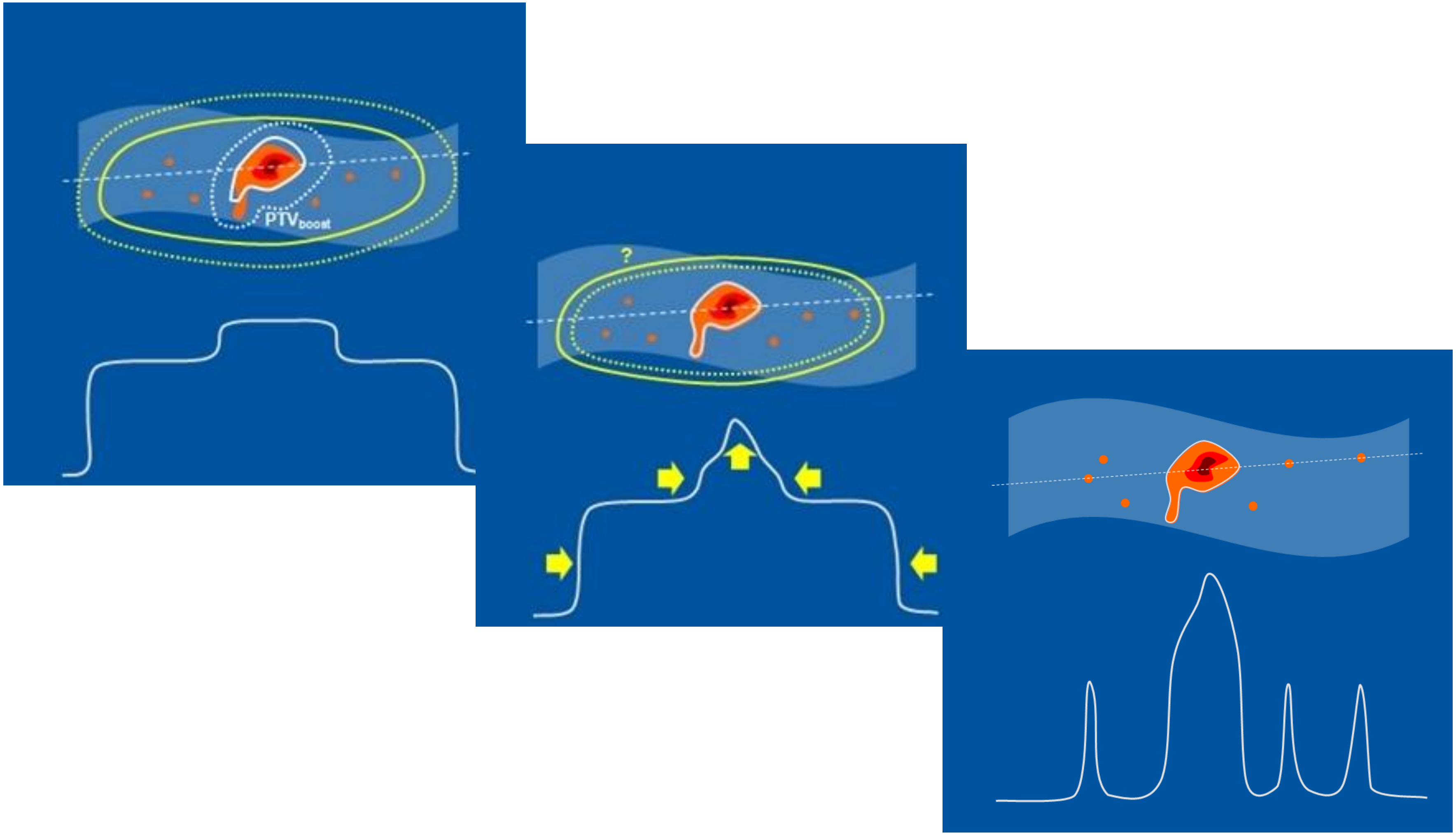
Seeing what you treat

- Soft tissue
- On-line
- Real time



Bringing certainty in the actual treatment

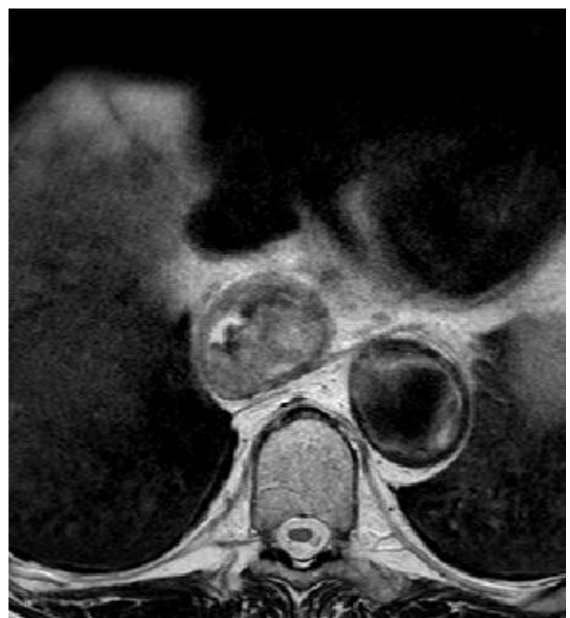
Improve local control, minimize NTCP, by tailored dose escalation

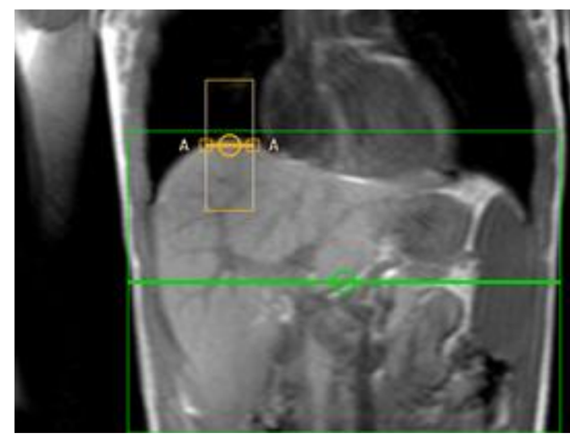


T2 weighted protocol oesophagus

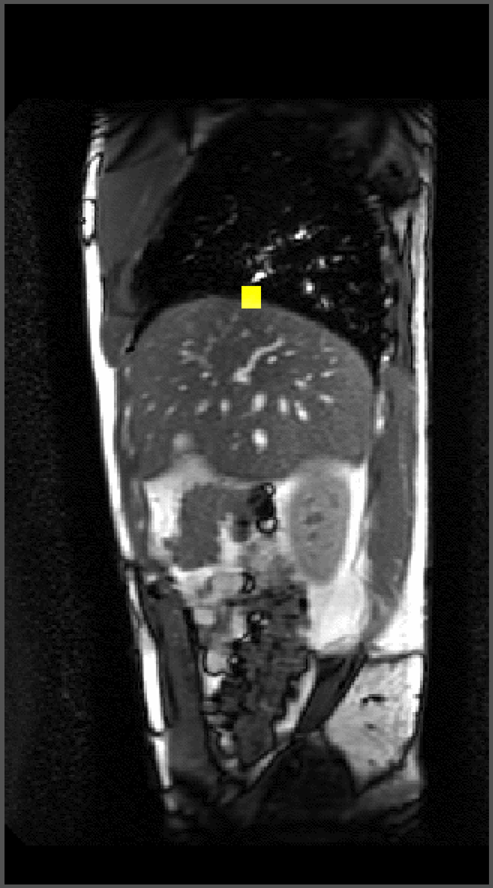
Expert panel repeatedly decided on protocol that provided best imaging quality in combination with acceptable acquisition time

- no cardiac triggering
- respiratory motion compensation with the use of a navigator
- sagittal + transverse
- 2 x 5 minutes



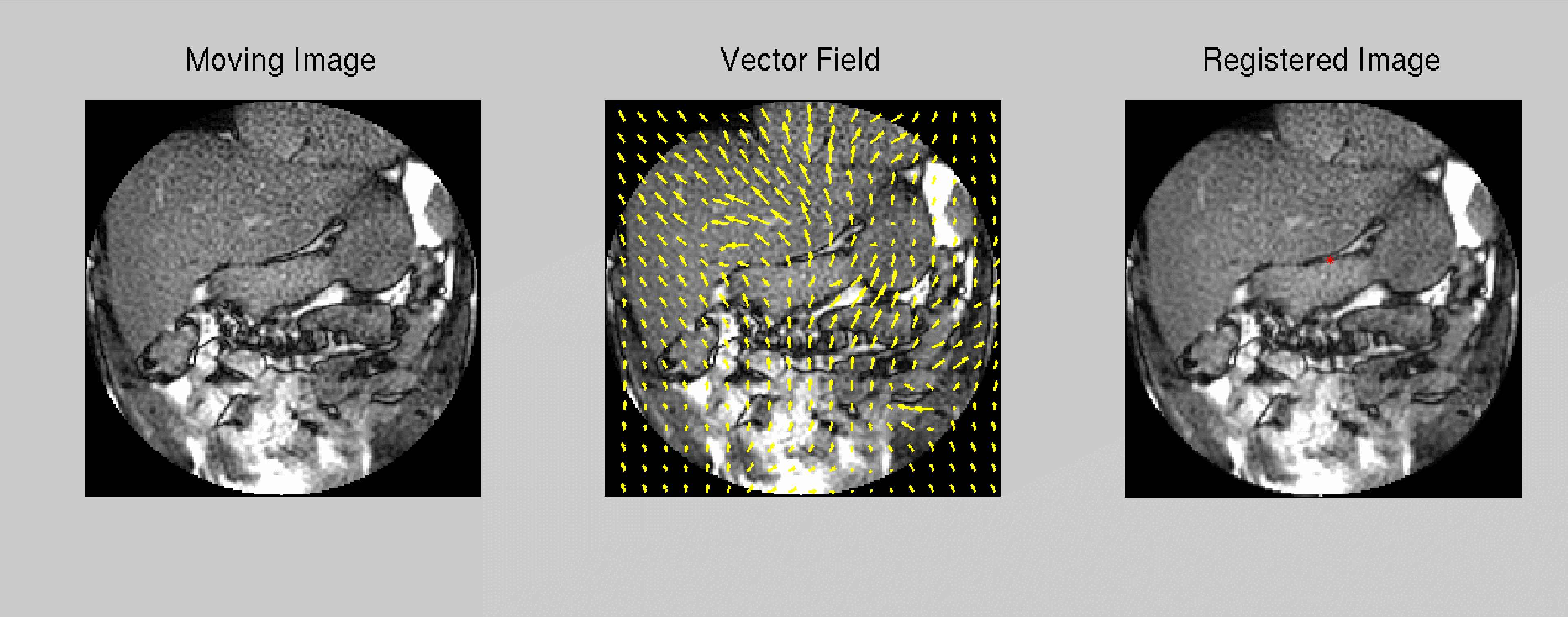


Liver, irregular breathing



Courtesy Anna Andreychenko

Pancreas: undersampled radial balanced SSFP



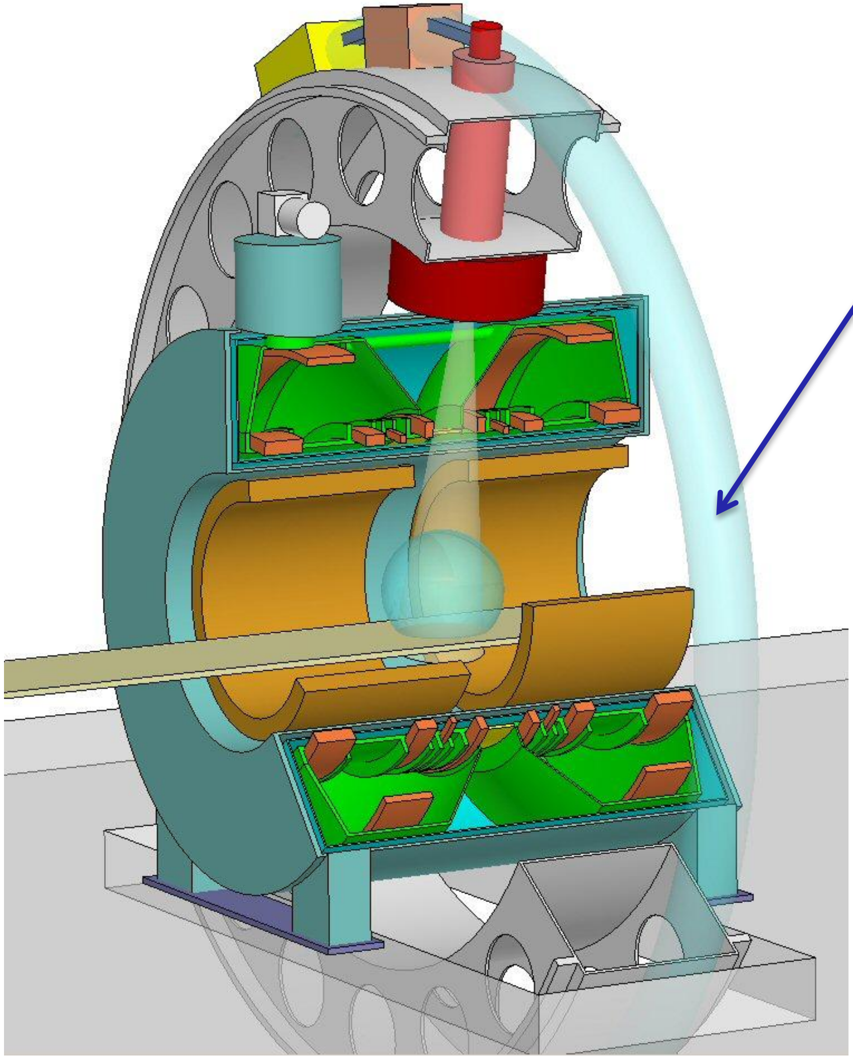
Thanks: Baudouin Denis de Senneville, UMCU HIFU Group

UMCU solution: Bringing certainty. Diagnostic Philips Ingenia with a Elekta accelerator

1.5T 70 cm bore Philips Ingenia

Lagendijk and Bakker, MRI guided radiotherapy - A MRI based linear accelerator
Radiotherapy and Oncology Volume 56, Supplement 1, September 2000, 220

Concept of MRI accelerator



Active shielding
Toroid of zero magnetic field
Decouples accelerator and MRI

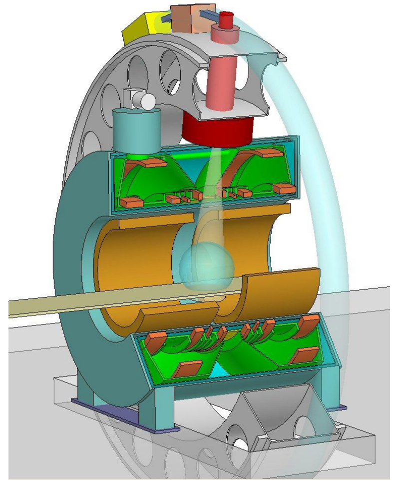
Development MRL

(collaboration UMCU, Elekta and Philips)

Radiotherapy and Oncology. Vol 56, Sup 1, Pages S1-S255, 2000, 19th Annual ESTRO Meeting
Istanbul, Turkey

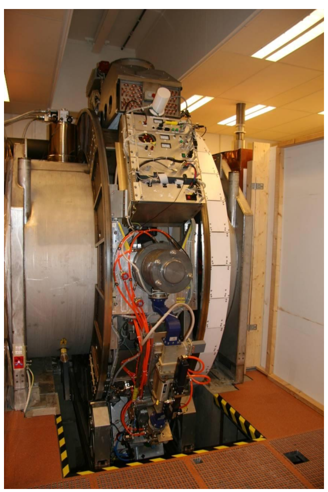
MRI guided radiotherapy: a MRI based linear accelerator. J.J.W. Lagendijk, C.J.G. Bakker

1999
invention



2004
design

2009
1st prototype

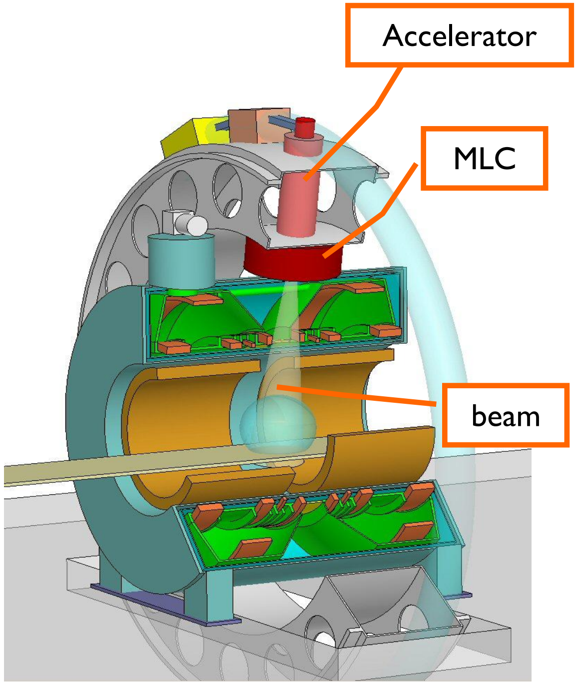


2012
2nd prototype

2015
Clinical grade prototype

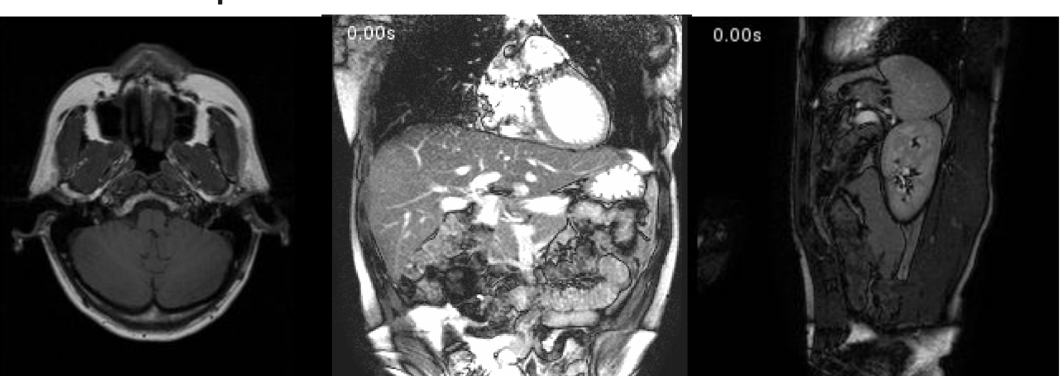
2016
Clinical prototype

First prototype MRL for MRI guided RT

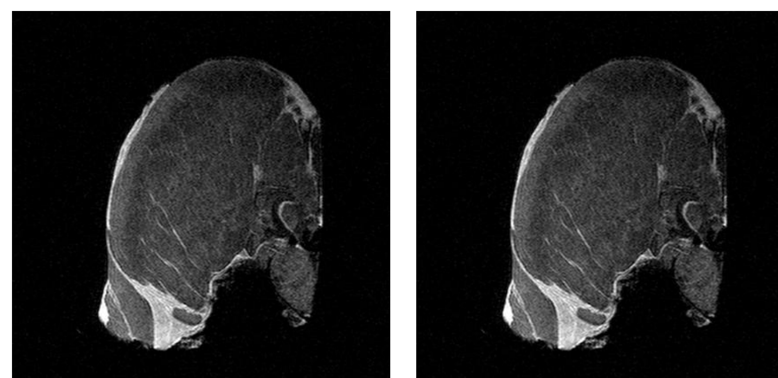


Artist impression

Prototype MRI accelerator

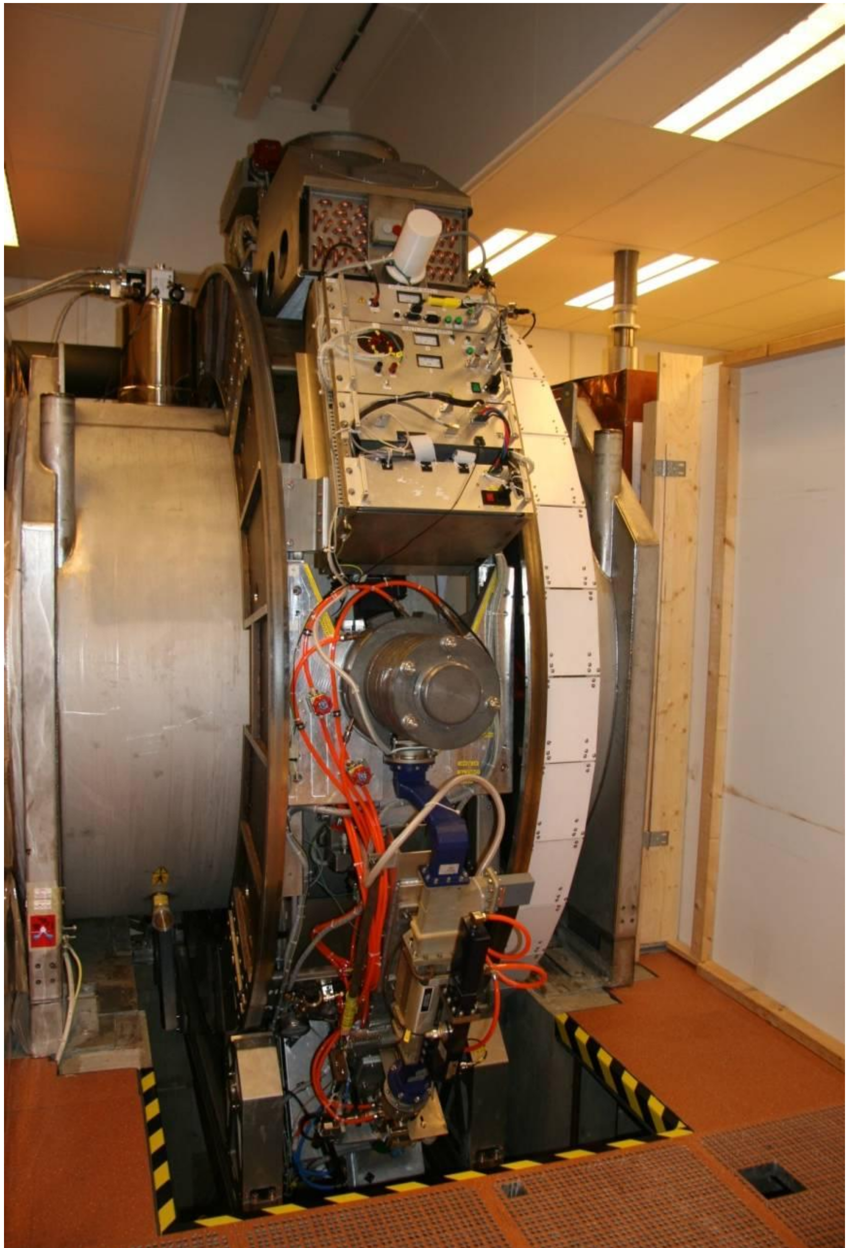


1.5 T diagnostic MRI quality

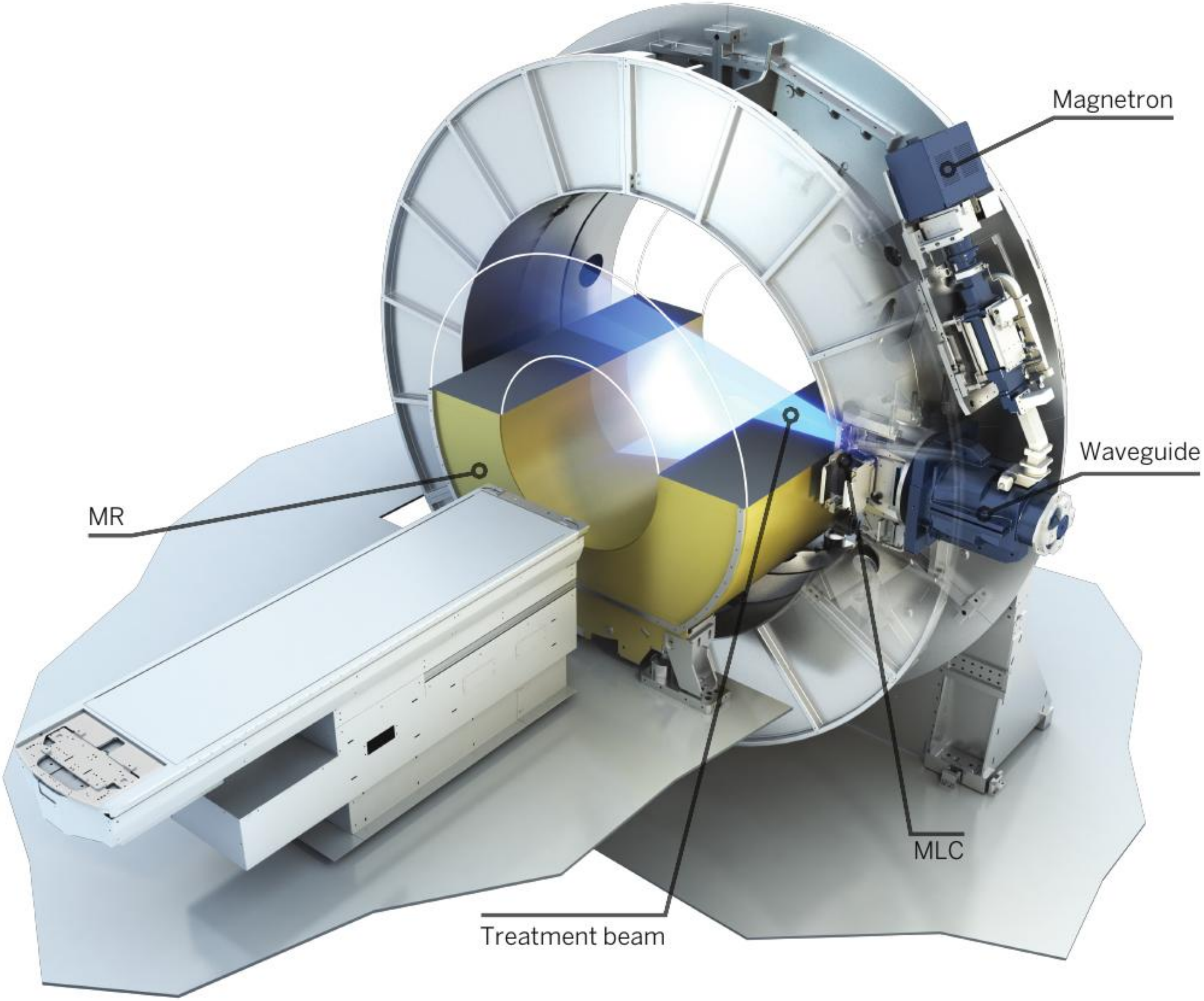


No impact of beam on MRI

MRI with ring gantry



Pre-clinical prototype in Utrecht

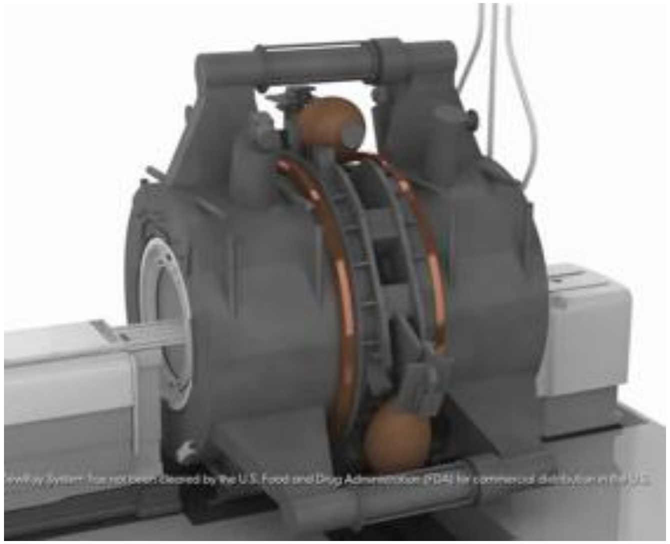


Magnet prototype at Philips Helsinki

Prototype MRI accelerator at the UMC Utrecht

Elekta press release 22 January 2015

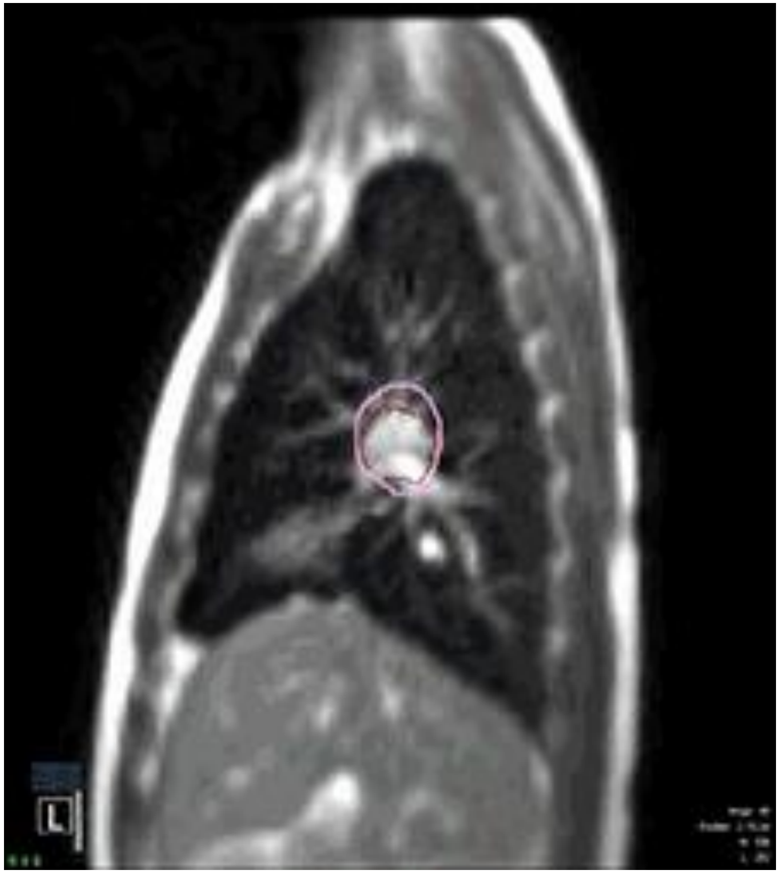
Viewray: 3x 60Co source



www.viewray.com

- 3x Co60 sources
- 0.3 T superconducting MRI
- Siemens MRI back-end

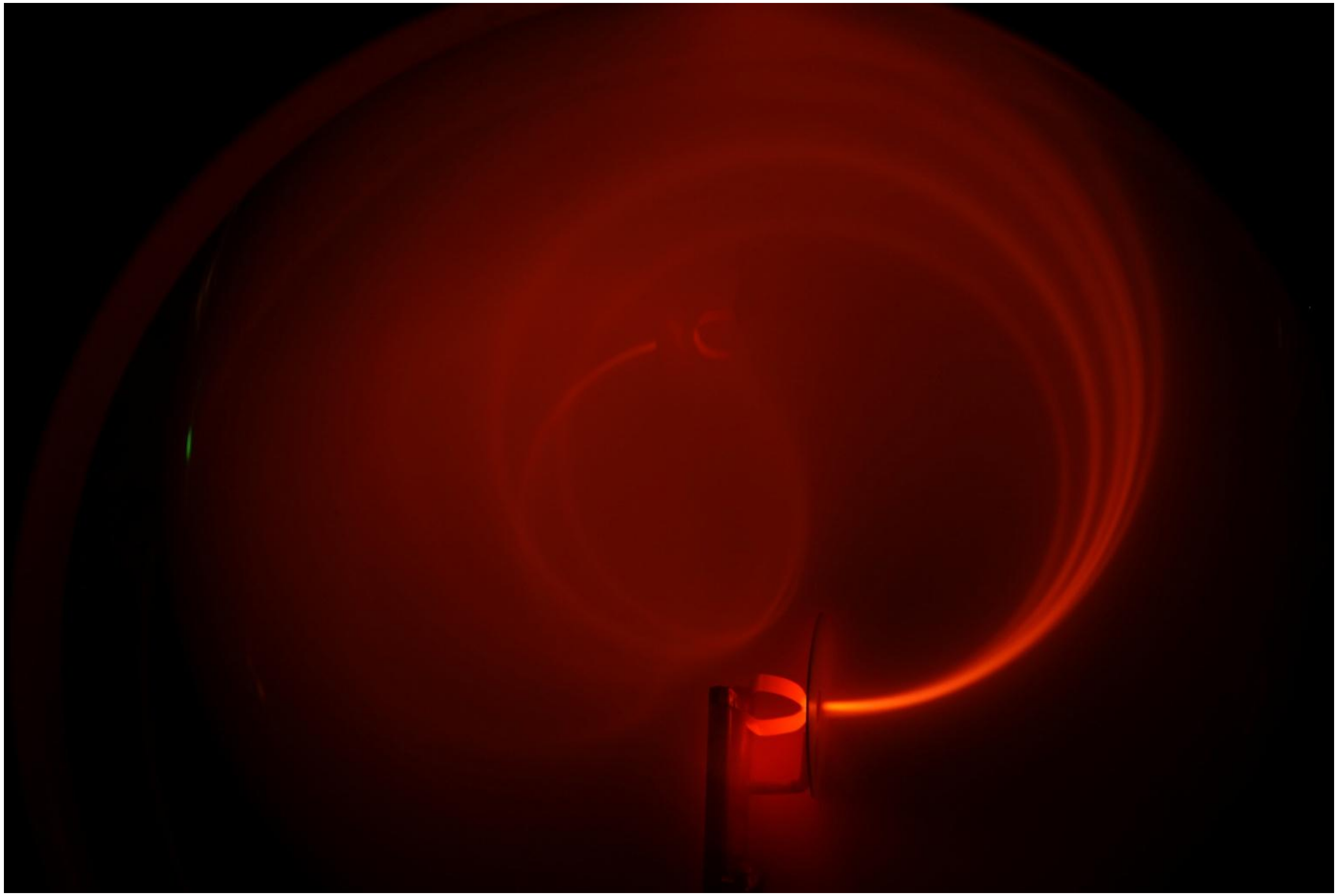
Viewray: 3x 60Co source



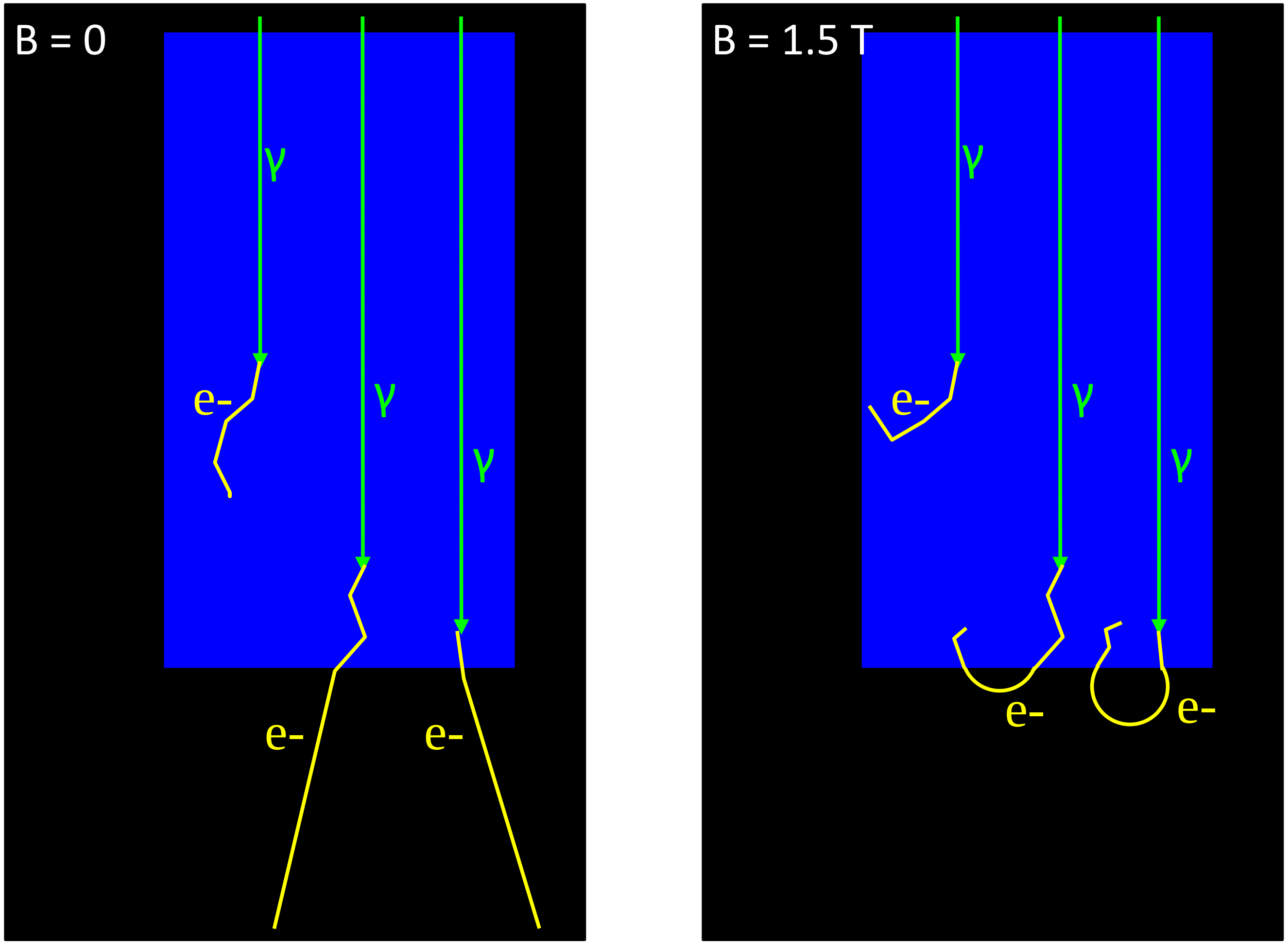
System in clinic at St. Louis
Siteman Cancer Center

Electrons in a magnetic field: Lorentz force

Different energy
Field strength → Different radius

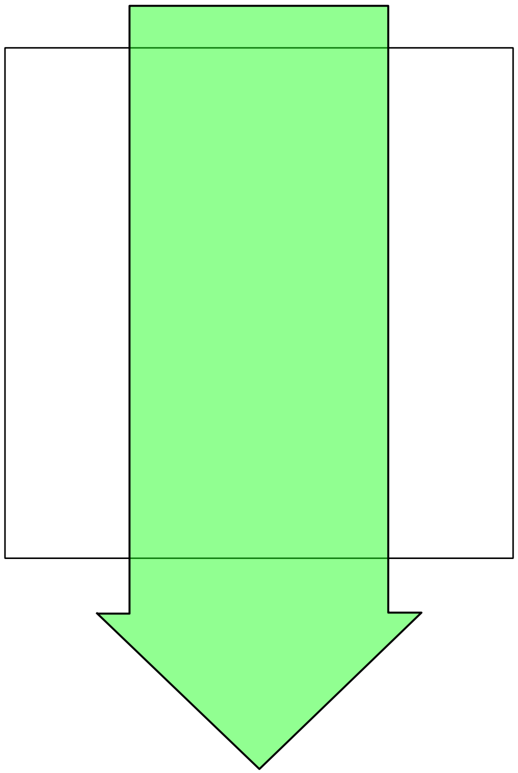


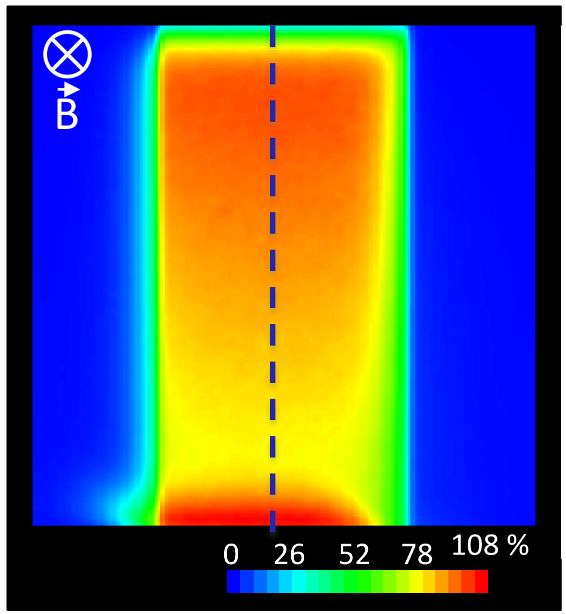
Dose deposition in a magnetic field: The Electron Return Effect (ERE)

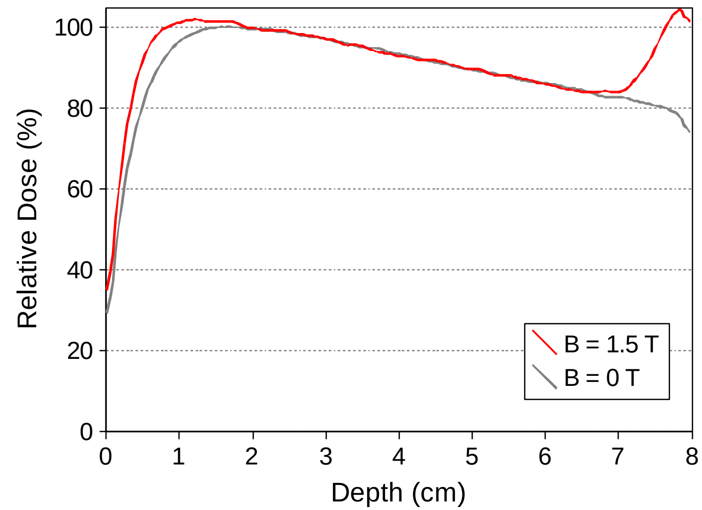


The Electron Return Effect (ERE)

ERE (Electron Return Effect)



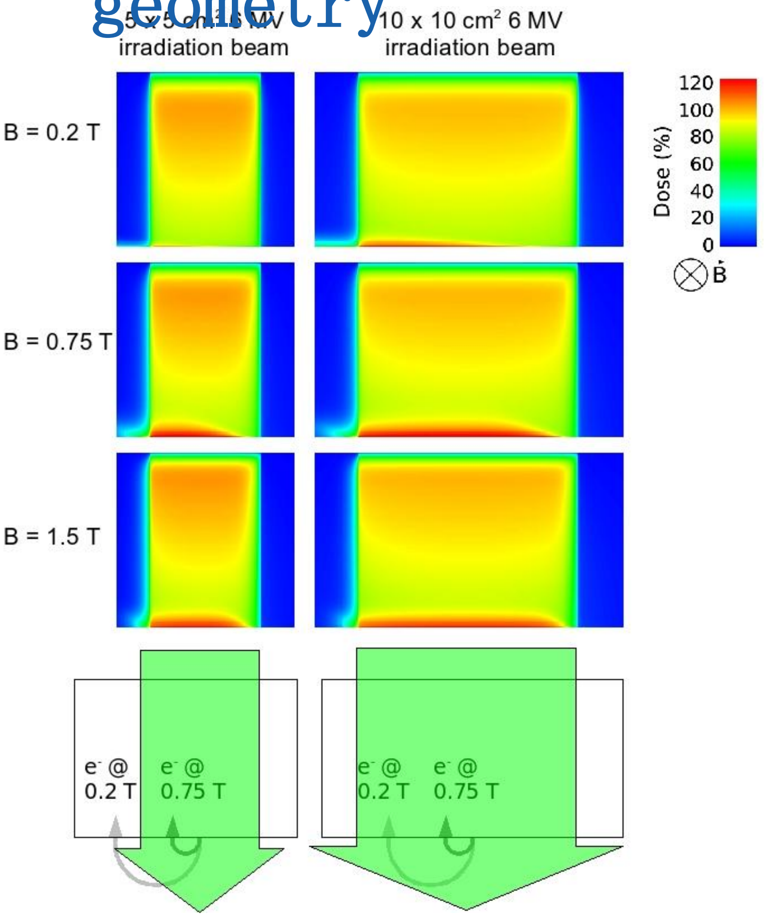


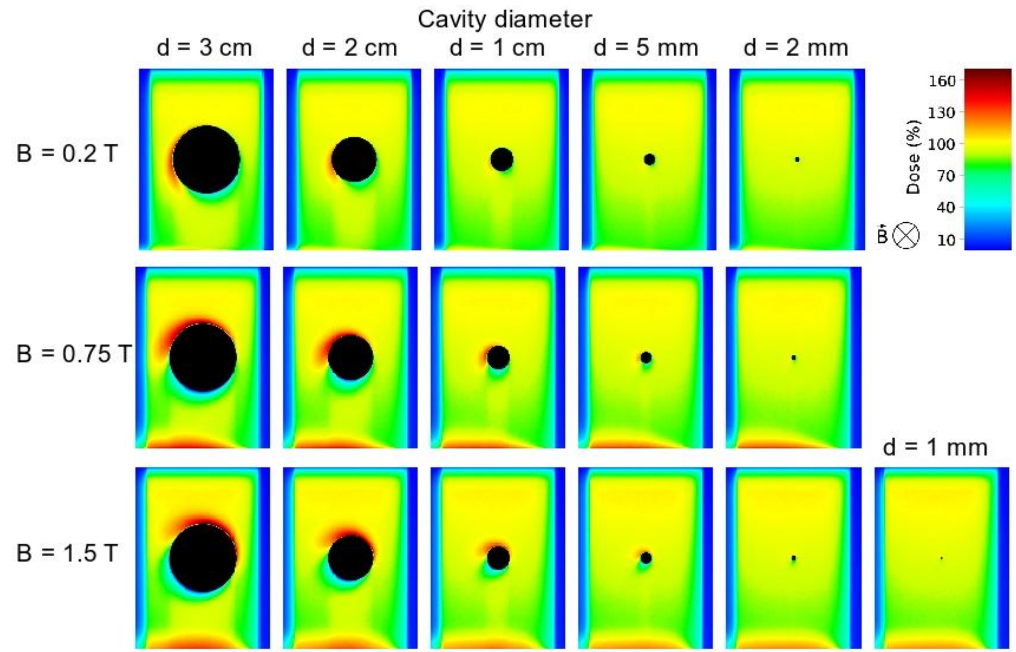


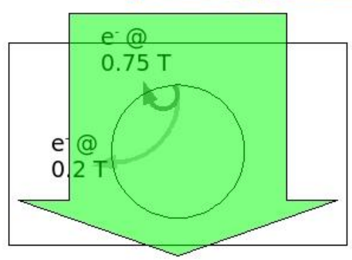
Dose effects at all tissue-air boundaries

From Raaijmakers et al. PMB 2005

Impact is depending of: Field size, B-field strength, tissue density and geometry

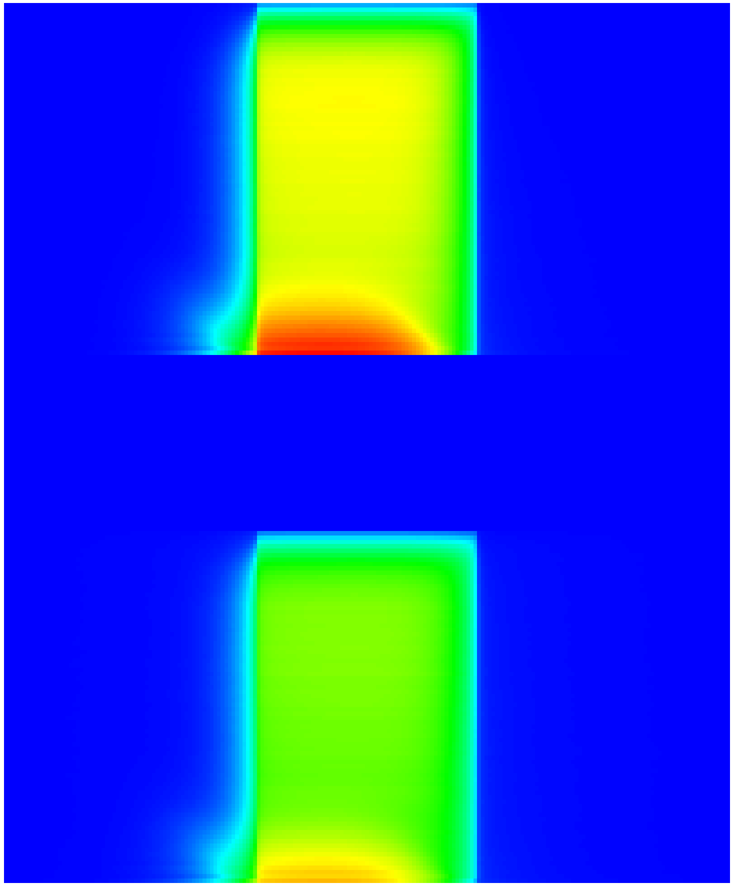


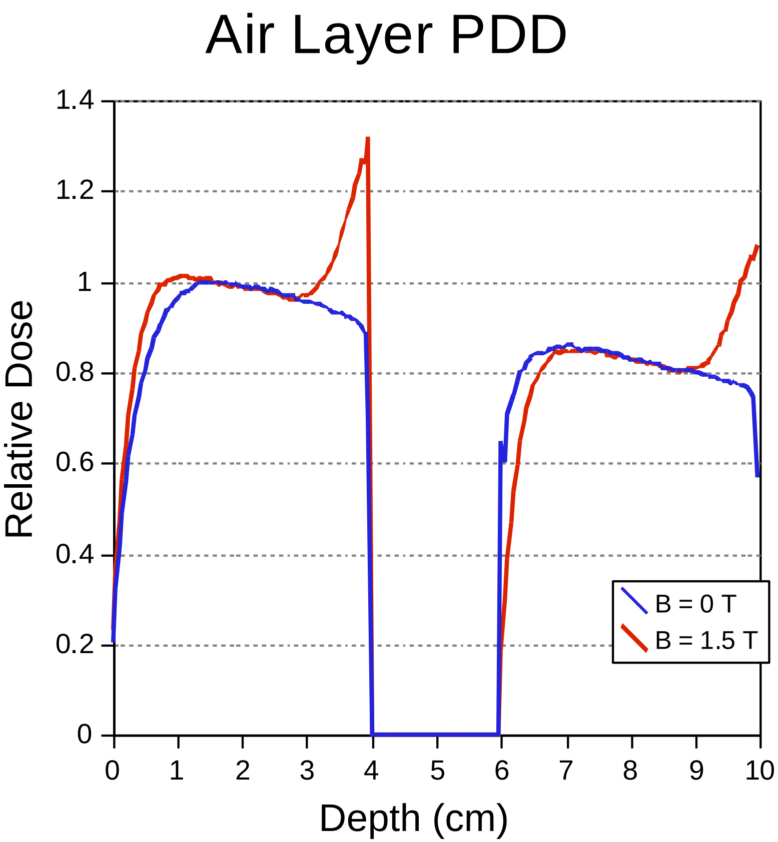




	Magnetic field strength		
Electron energy (MeV)	0.2 T	0.75 T	1.5 T
0.5	14.5	3.9	1.9
1	22.7	6.3	3.2
1.5	32.4	8.6	4.3
2	41.0	10.9	5.5

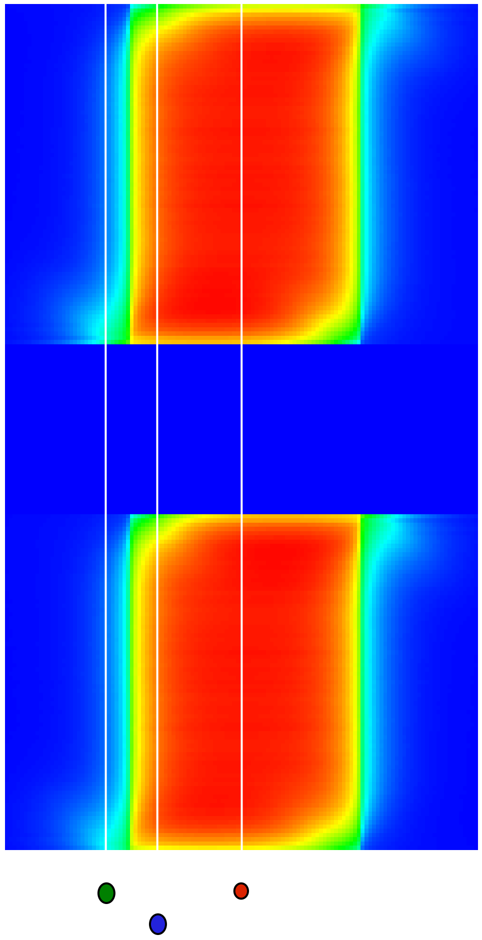
Electron Return Effect (ERE)

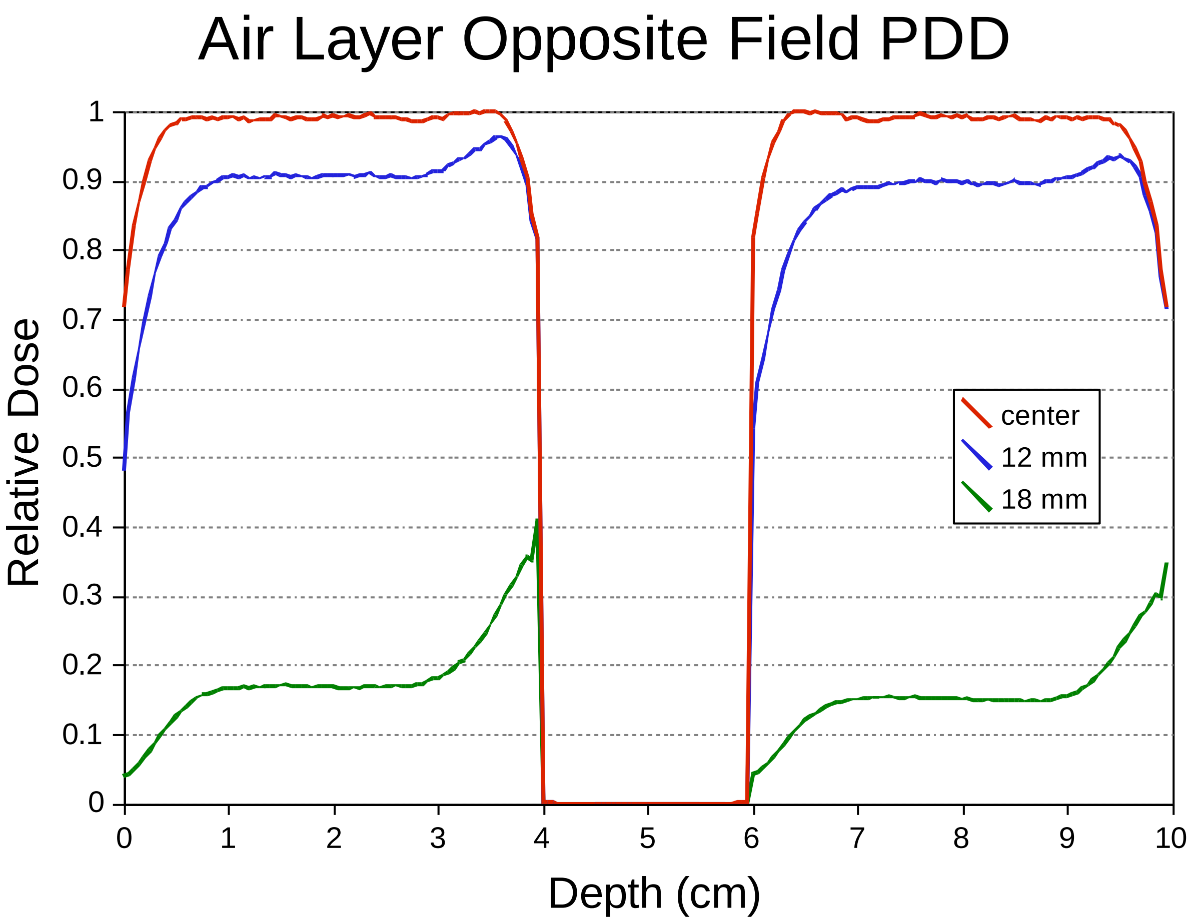




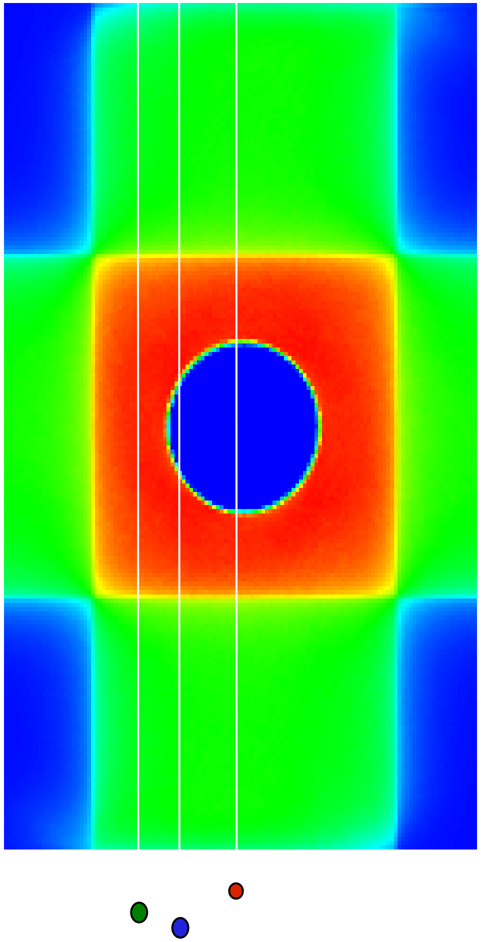
Increased dose deposition at tissue-air interface: Electron Return Effect (ERE)

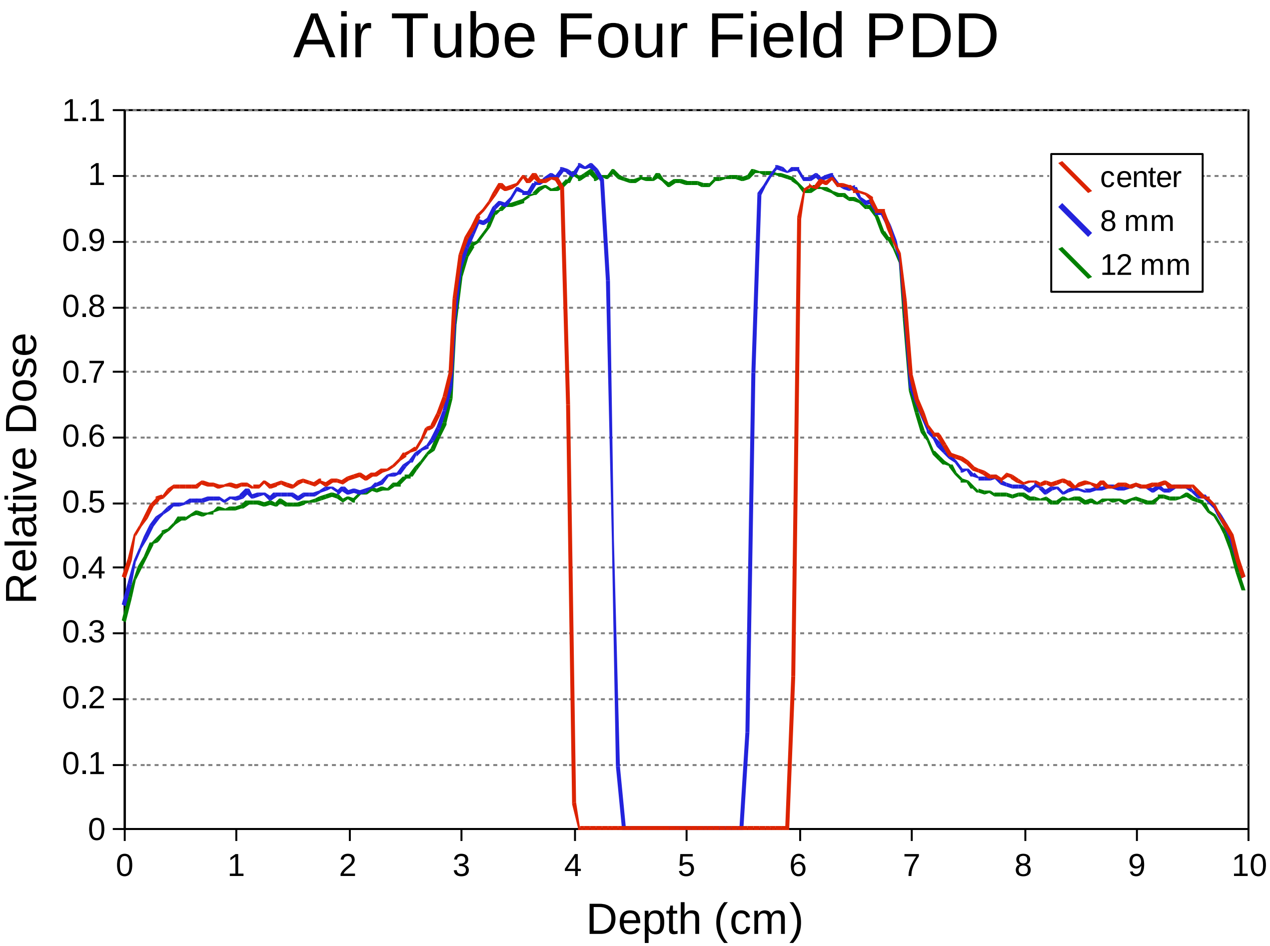
ERE compensation with opposing beams



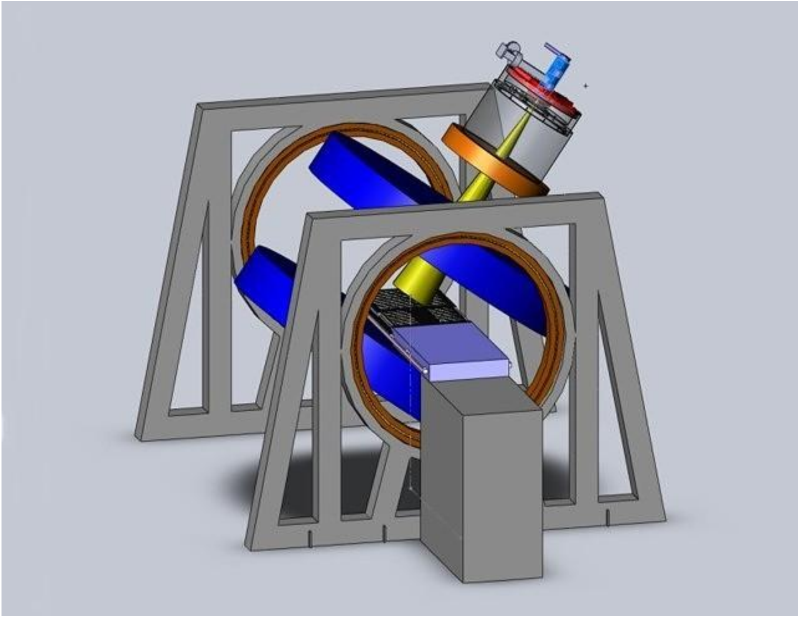


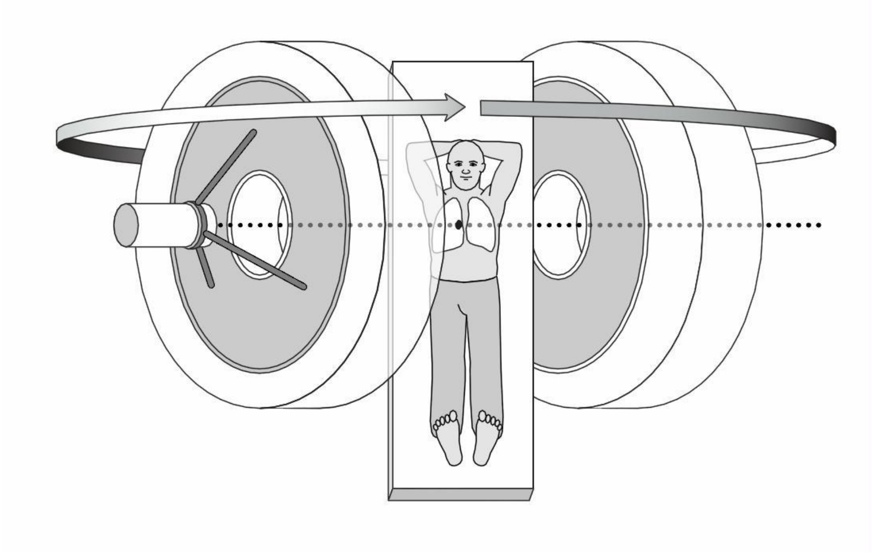
ERE compensation with four beams





B field parallel to beam





- From Fallone, Cross Cancer Center, Alberta, Canada
- From Paul Keall, Stanford Univ., USA

Electron trajectories in longitudinal B field

- From Bielajew, Med Phys 20(4), 1993
- 20 MeV electrons in water
- 0, 6 and 20 T B field

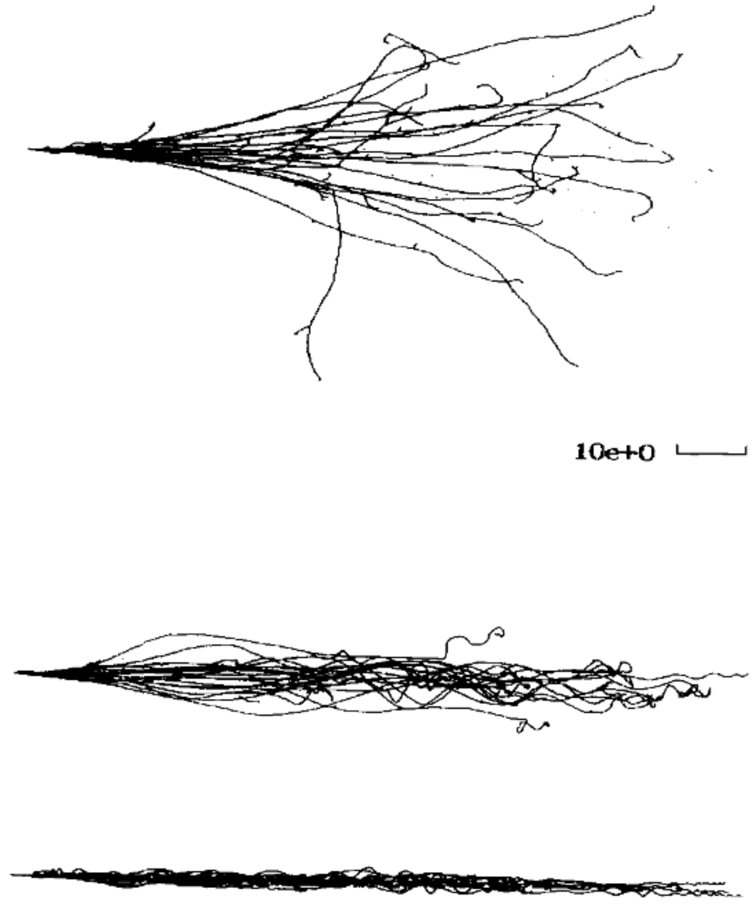
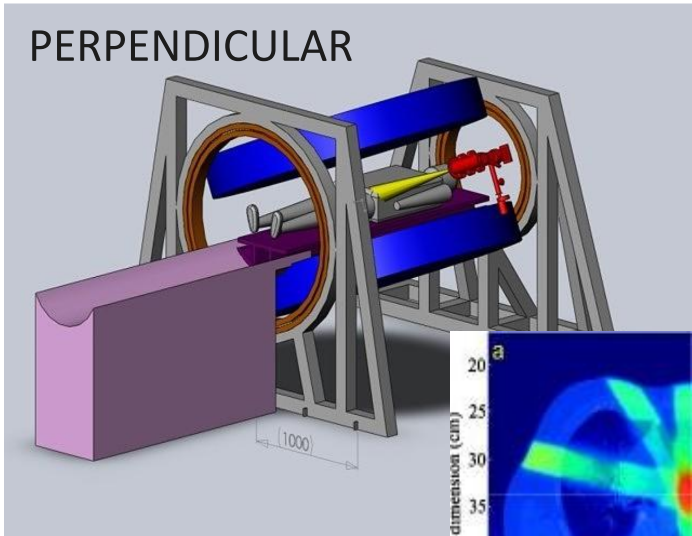
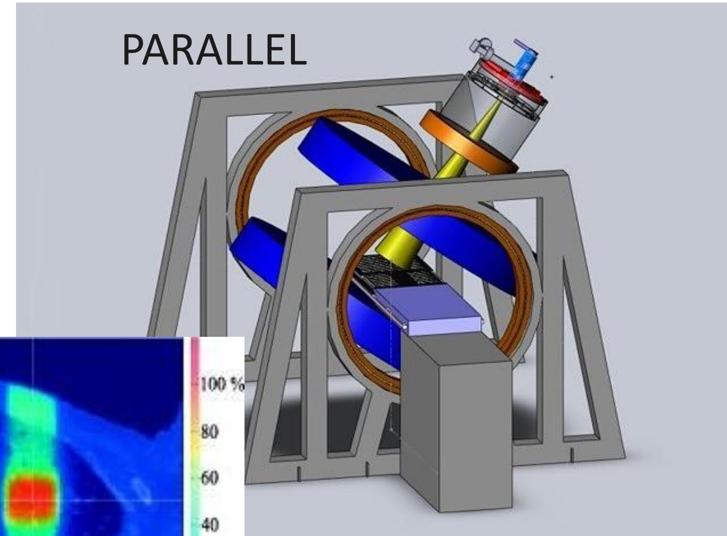
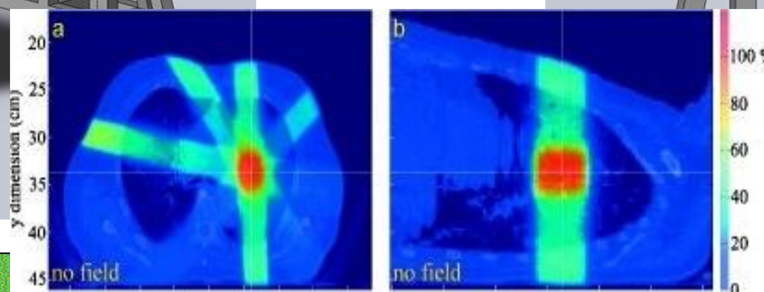


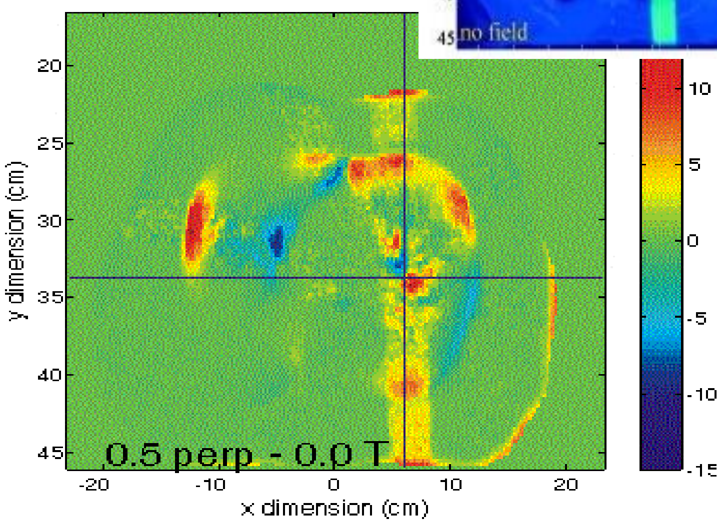
FIG. 1. Twenty histories of 20-MeV electrons are transported through water in the presence of uniform, longitudinal magnetic fields. Top: 0 T, middle; 6 T; bottom: 20 T. The range of 20-MeV electrons in water is about 9.3 cm, and this is the longitudinal extent of the trajectories depicted. A 1-cm scale marker is also shown.

Difference for dose in perpendicular or parallel magnetic field

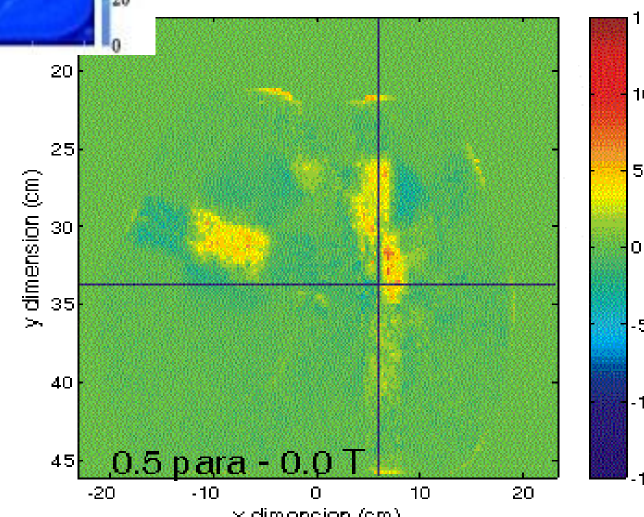






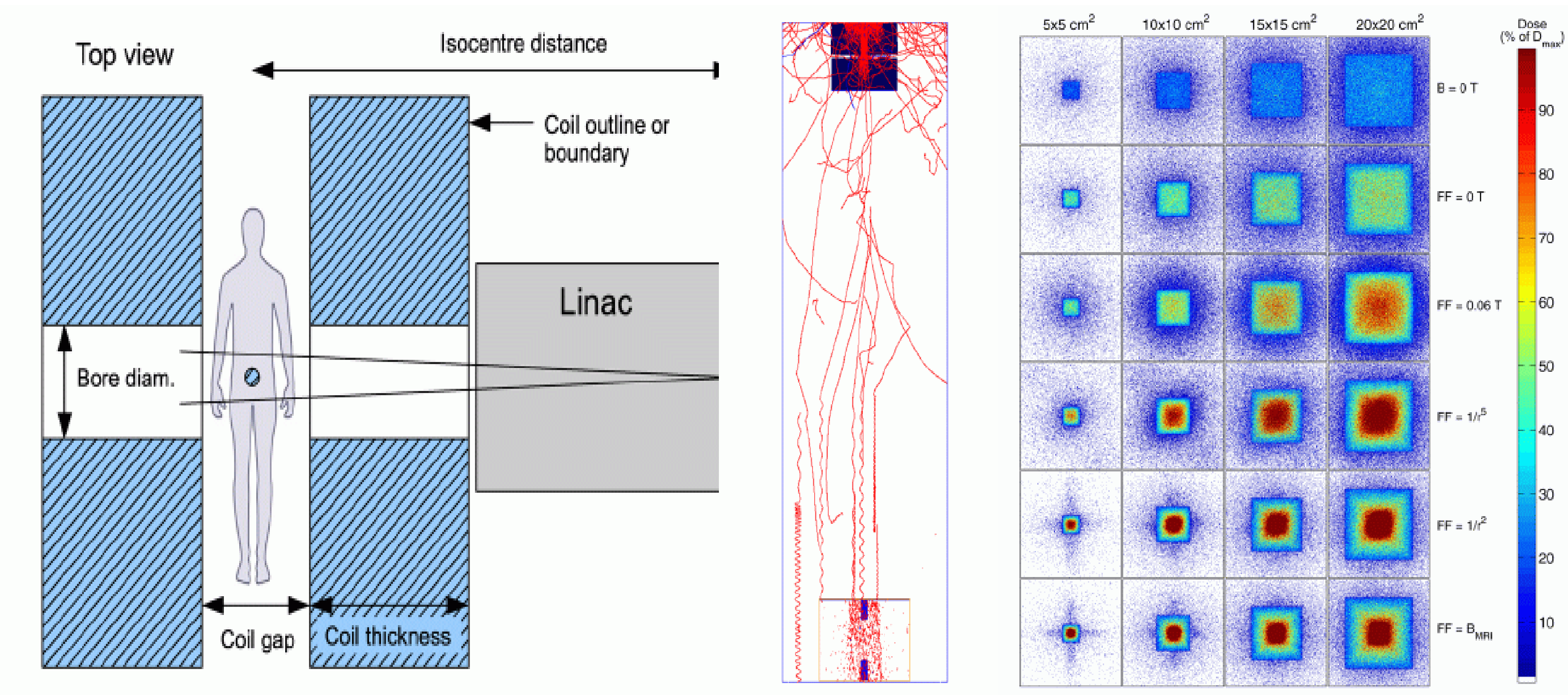


0.5 T



Fallone et al.: Cross Cancer Institute, Alberta Canada www.linac-MR.ca

Electron contamination for longitudinal B fields by ionisation of air column

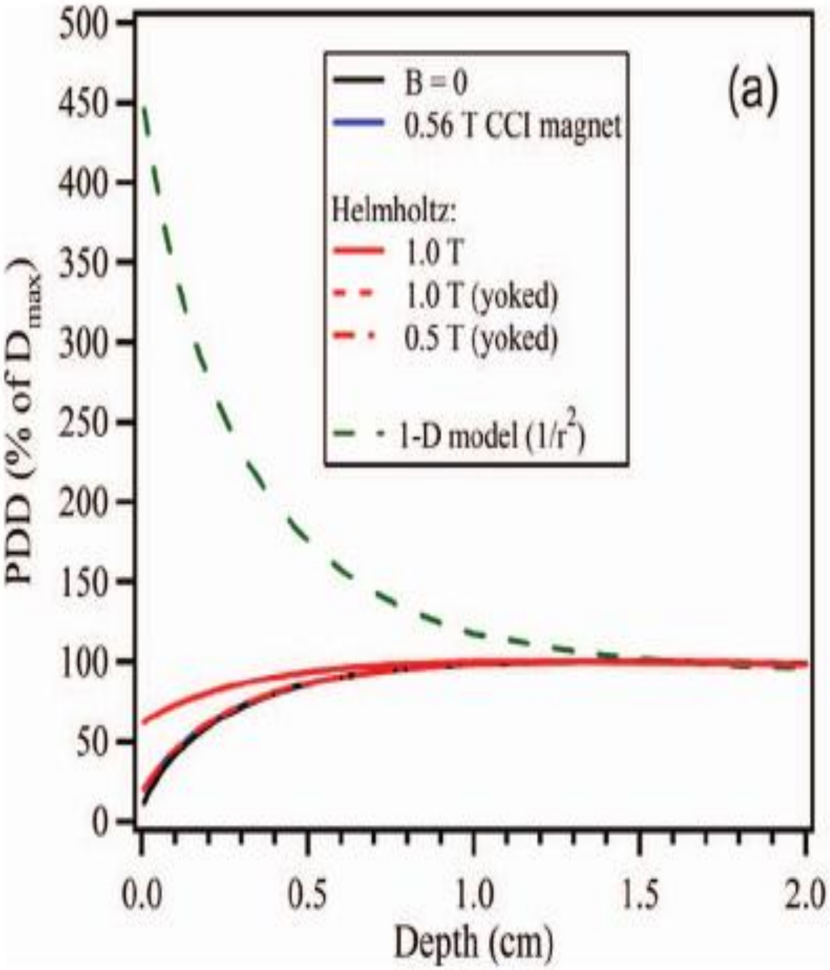


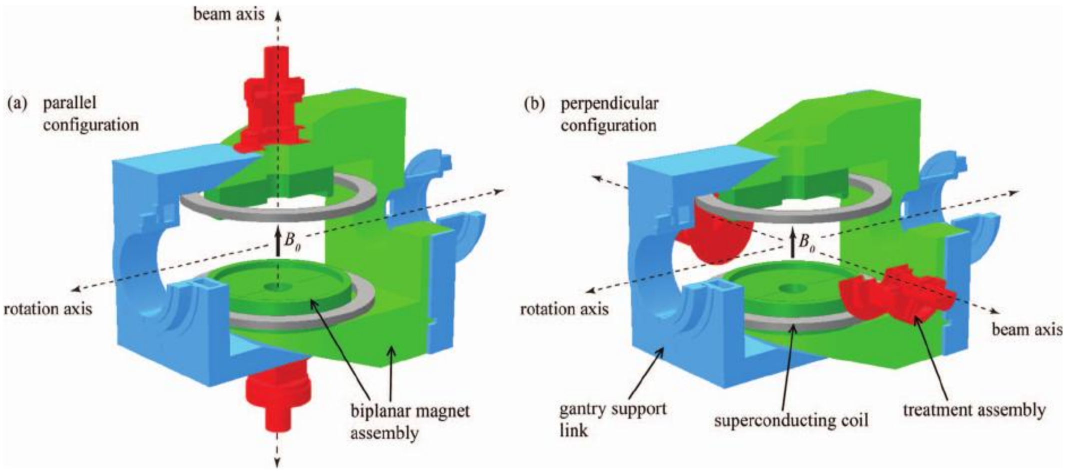
(c) 40 cm Coil, $B_{FF} = 0$ T

(b) 40 cm coil

From Oborn et al., Med. Phys(39)2, 2012

Electron contamination for longitudinal B depends on exact fringe field





Keyvanloo et al., Med. Phys(39)10, 2012

There is no position verification available

- On-line and real-time treatment planning
  - Translations
  - Rotations
  - Deformations
  - Regression
  - Etc.

Some physics research lines MRI guided Radiotherapy

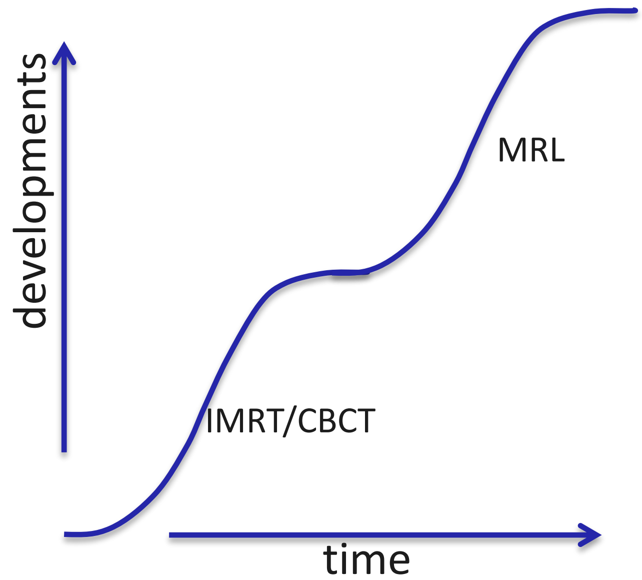
- Tumour visualization, MRI sequence development
  - Is what we see tumour and all tumour present
  - Is there a CTV and how far does it reach
- Is the anatomy stable?
  - Real time visualization and 4D tissue models
- Can we deal with non stable anatomy?
  - Real time movement/deformation management
  - Gating/tracking
- On-line and real time treatment planning
- Dosimetry and QA
- Dose accumulation

Some clinical research lines MRI guided Radiotherapy

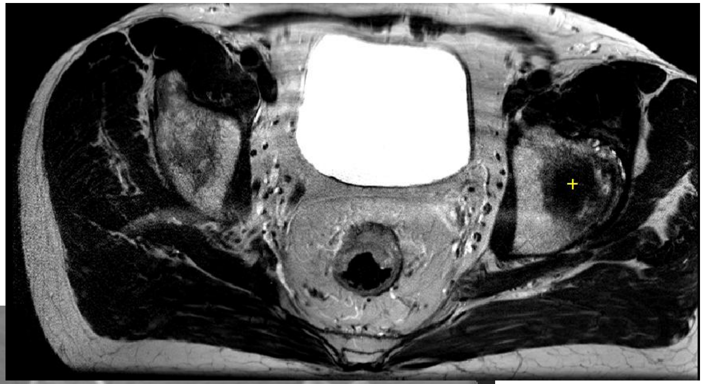
- Tumour characterization
  - Is what we see tumour and all tumour present
  - Is there a CTV and how far does it reach
- What dose distribution must be applied. Dose painting? Tumour presence/volume and tumour characterization
- OAR avoidance. What NTCP do we expect, volume dependency
- Treatment procedures
- Can we optimize the anatomy?
  - Interventional treatment procedures
- Treatment response assessment

What do we expect using the MRL:

- Much better on-line tumour definition, GTV boost
- Tumour characterization, heterogeneity, dose painting
- Excellent normal tissue definition, avoidance
- Hypofractionation
- Intervention
- Certainty in the treatment process and thus learning
- Oligo-metastases, repeated treatments
- Less biology, more targeting
- Less protons, more MRI linacs
- Better local control
- Less NTCP
- Less surgery more radiology



Next innovation curve in RT



Clinical introduction

MR-Linac Clinical Consortium: ATLANTIC

- **UMC Utrecht* (Utrecht)**
- **MD Anderson (Houston)**
- NKI-AvL (Amsterdam)
- MCW (Milwaukee)
- Sunnybrook (Toronto)
- Royal Marsden-ICR (London)
- Christie (Manchester)

Consortium clinical studies

First in man trial: spinal bone mets (safety and feasibility study) UMCU

Clinical studies prioritization list:

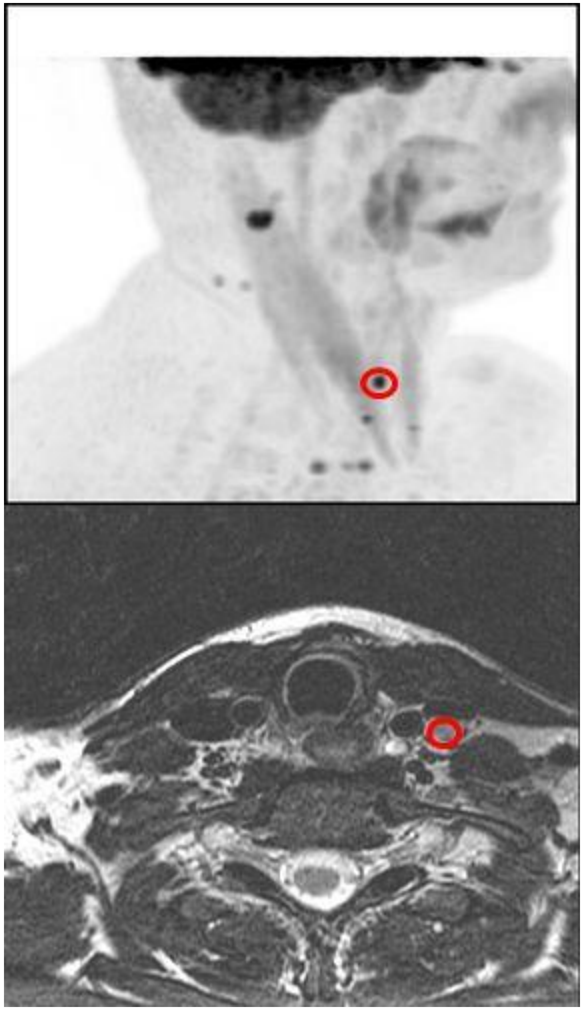
- Brain
- Breast
- Cervix
- Esophagus
- Rectum
- Lung
- Oropharynx
- Pancreas
- Prostate

Coordination: Marco van Vulpen and Linda Kerkmeijer (UMCU)

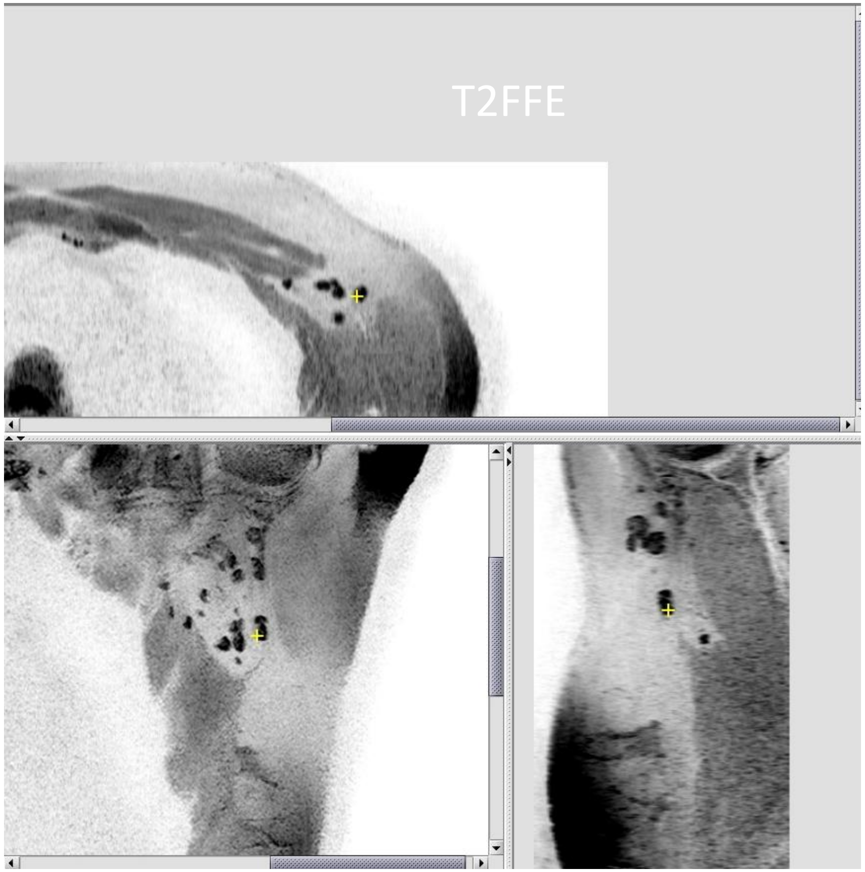
Clinical steering committee: Marco van Vulpen (UMCU), Marcel Verheij (AvL), Kevin Harrington (MH-ICR), Ananya Choudhury (Christie), Dave Fuller (MDACC), Chris Schultz (F&MCW), Arjun Sahgal (Sunnybrook), Joel Goldwein and Kevin Brown (Elekta)

MRL in 2025

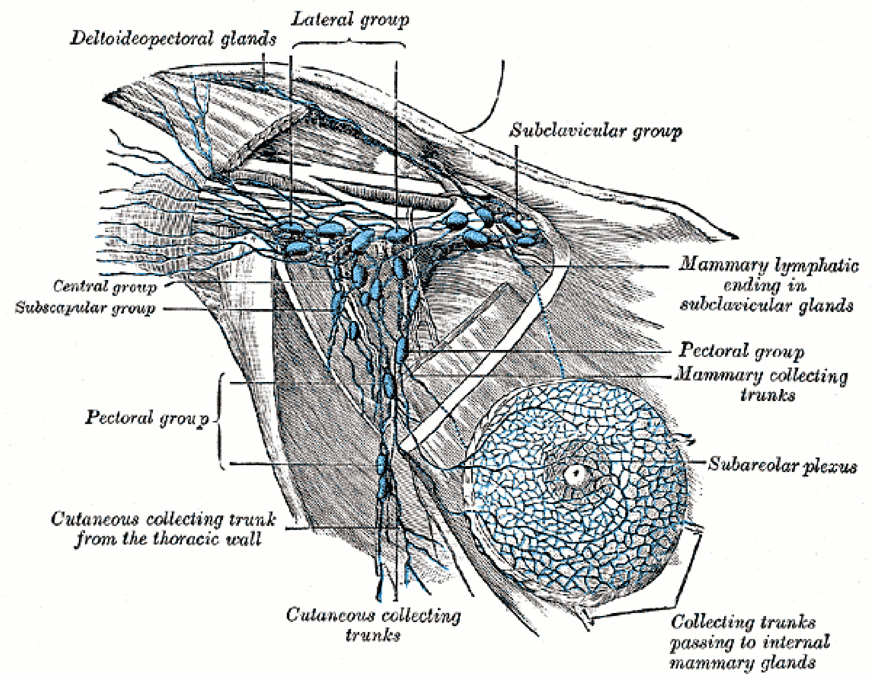
- 4D MRI
- Optimization imaging quality (3T, fingerprinting, MRI/PET, etc.)
- Focus on imaging, question what to treat
- Robot approach: real time treatment planning and dose delivery (automatic, slave, high resolution MLC, etc)
- Clinical process like an intervention



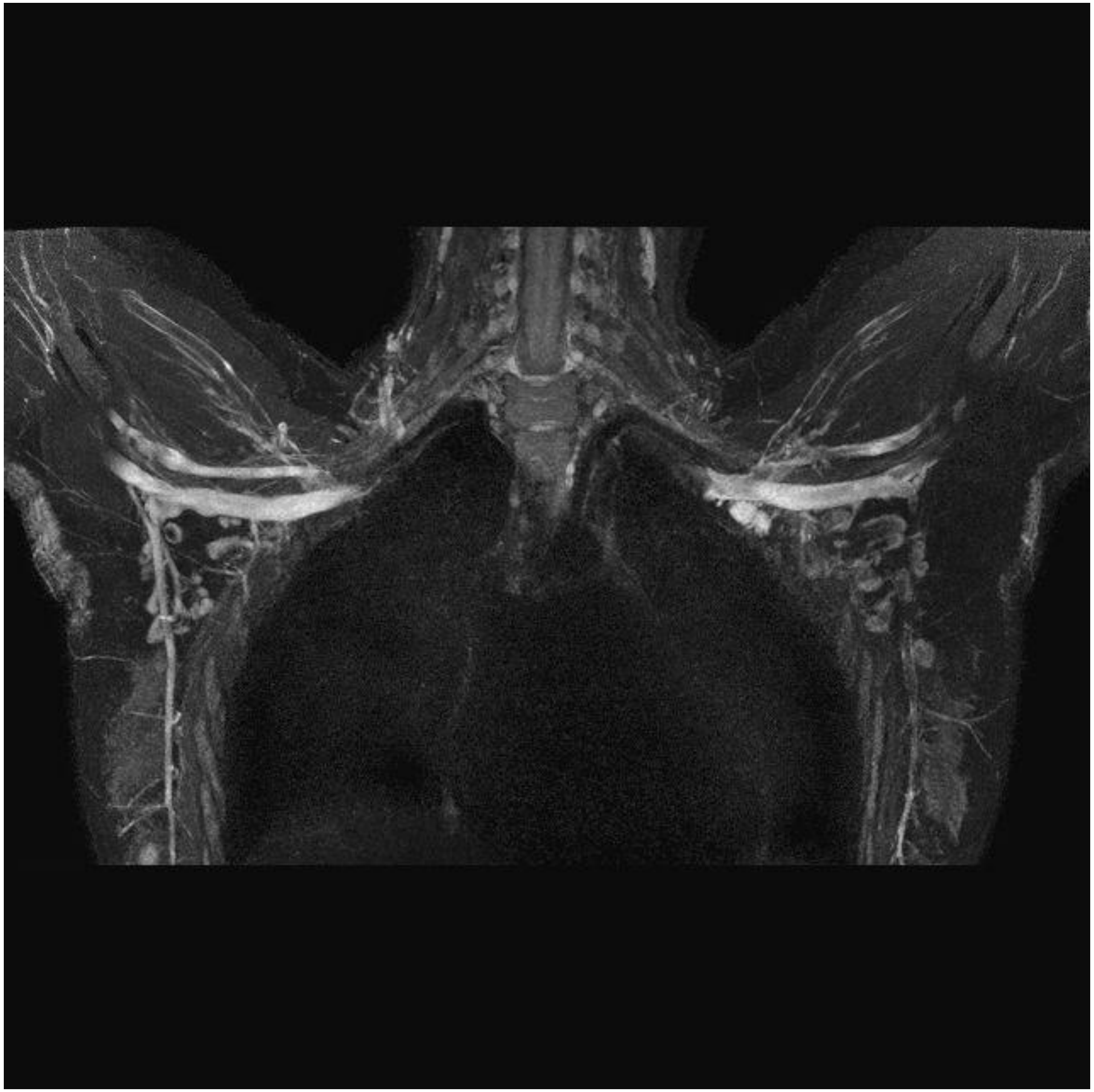
3D T2FFE image quality



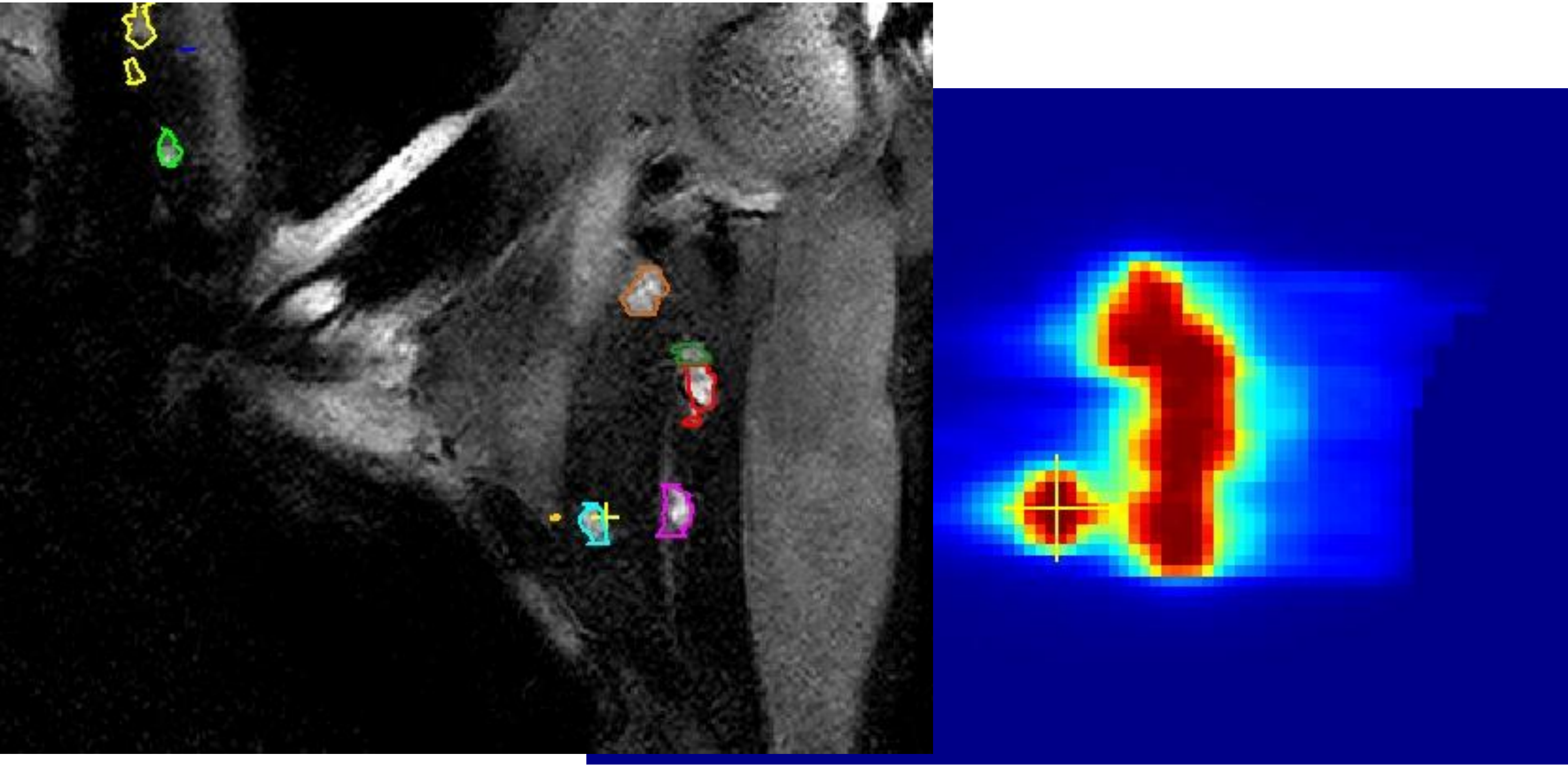
Next step is finding lymph vessels to define which nodes are related to arm only



Search for the lymph vessels



Stereotactic boost individual lymph nodes



Courtesy Tristan van Heist

Radiotherapy goes MRI

(Radio)therapy UMC Utrecht goes MRI

- Tumour characterization
- MRI simulation: delineation
- MRI guidance
  - MRI treatment guidance external beam
  - MRI guided brachytherapy
  - MRI guided HIFU
  - MRI guided protons
  - MRI guided radioembolization
- MRI treatment response assessment

7 MRI systems for therapy


CT
CT
CT
CT
CT
CT
CT
CT
CT
U7
U8
U6
U1
U2
U3
Ingang
U bent hier
Informatie
Wachten
Koffie Corner
Publiek toegangelijk - wachten
Toiletten
Radiotherapie
Ondersteuning
Parkeren


CT
CT
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CT
MRI
MRI
MRI
MRI
MRI
MRI
MRI
U7
U8
U2
U3
Ingang
U bent hier
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Wachten
Koffie Corner
Publiek toegangelijk - wachten
Toiletten
Radiotherapie
Ondersteuning
Parkeren

Conclusion

- (Radio)Therapy becomes MRI guided
- Better local tumour control
- Less toxicity
- Less invasive: surgery without a knife

Major collaboration UMCU and industry:

- Elekta
- Philips

CIGOI is part of the UMCU Centre for Image Sciences

- >150 PhD students (>80% with MRI in the title)
- >35 residents (radiology, radiotherapy and clinical physics)
- 13 full professorships (therapy and radiology)
- Earning power >6 Mlj€ a year
- 8x postgraduate courses

- Collaboration major industry: Philips, Elekta
- From invention/co-creation → clinical product/clinical introduction → clinical evaluation
- From hard-core physics/mathematics to clinic

Acknowledgement

Physics Team MRI in RT UMCU

- Anna Andreychenko
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- Sara Hackett
- Sophie Heethuis
- Tristan van Heijst
- Stan Hoogcarspel
- Jean-Paul Kleijnen
- Charis Kontaxis
- Alexis Kotte
- Astrid de Leeuw
- Astrid van Lier
- Hans Ligtenberg
- Mariska Luttje
- Stefano Mandija
- Matteo Maspero
- Gert Meijer
- Rien Moerland
- Christel Nomden
- Marielle Philippens
- Mathew Restivo
- Niels Raaijmakers
- Bas Raaymakers
- Alessandro Sbrizzi
- Rob Tijssen
- Tim Schakel
- Yulia Shcherbakova
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- Kimmy Smit
- Bjorn Stemkens
- Jochem Wolthaus
- Simon Woodings
- Cornel Zachiu
- Loes van Zijp

Clinical Team MRI in RT UMCU

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- Mariska den Hartogh
- Hanne Heerkens
- Martijn Intven
- Lisanne Jager
- Linda Kerkmeijer
- Irene Lips
- Juliette van Loon
- Metha Maenhout
- Max Peters
- Peter van Rossum
- Ina Schulz
- Chris Terhaard
- Joanne van der Velden
- Marco van Vulpen
- Danny Young-Afat

Is there a difference in required dose to sterilize the CTV shell around the GTV or the GTV itself:

- 29% A. No, a homogeneous dose is required over the whole volume
- 6% B. Yes, the GTV needs twice the dose
- 52% C. Yes, the GTV needs about 20-30% more dose
- 14% D. Only the centre of the GTV needs the highest dose

Is there a difference in required dose to sterilize the CTV shell around the GTV or the GTV itself:

A. No, a homogeneous dose is required over the whole volume
B. Yes, the GTV needs twice the dose
C. Yes, the GTV needs about 20-30% more dose
D. Only the centre of the GTV needs the highest dose

Starting point: Point counterpoint discussion: Med. Phys. 42, 2753 (2015)

What is true:

- 11% A. 4D cone beam gives real time information
- 26% B. 3D MRI is real time
- 46% C. MRI navigators can run at 50Hz
- 17% D. Binning CT or MRI data gives real time information

What is true:

A. 4D cone beam gives real time information
B. 3D MRI is real time
C. MRI navigators can run at 50Hz
D. Binning CT or MRI data gives real time information

MRI guided radiotherapy requires:

50%	1.	On-line treatment planning
9%	2.	EPID dosimetry for anatomy verification
41%	3.	High B0 field for tumour characterization

MRI guided radiotherapy requires:

A. On-line treatment planning
B. EPID dosimetry for anatomy verification
C. High B0 field for tumour characterization

The Electron Return Effect (ERE):

14%	A.	Is highest at skin beam entrance
62%	B.	Is highest at skin beam exit
20%	C.	Is neglectable at low (0.3T) magnetic field strength
4%	D.	Does not play a role in photon irradiation

The Electron Return Effect (ERE):

A. Is highest at skin beam entrance
B. Is highest at skin beam exit
C. Is neglectable at low (0.3T) magnetic field strength
D. Does not play a role in photon irradiation

Ref: Raaijmakers, A. J. E., B. W. Raaymakers, and J. J. W. Lagendijk. "Magnetic-field-induced dose effects in MR-guided radiotherapy systems: dependence on the magnetic field strength." Physics in medicine and biology 53.4 (2008): 909.