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Traceability and absorbed dose standards for small fields, IMRT and helical tomotherapy

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Outline

- Helical tomotherapy
  - what makes traceability difficult
- Alanine/EPR
  - a solution
- Results
  - alanine
  - ion chamber
- Further questions

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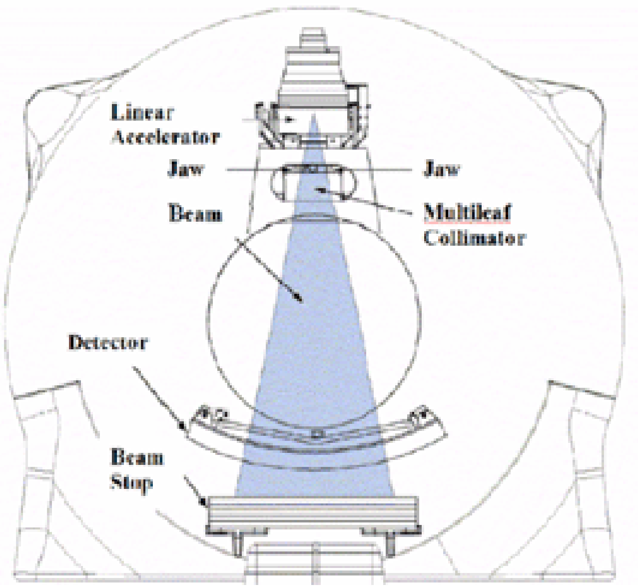
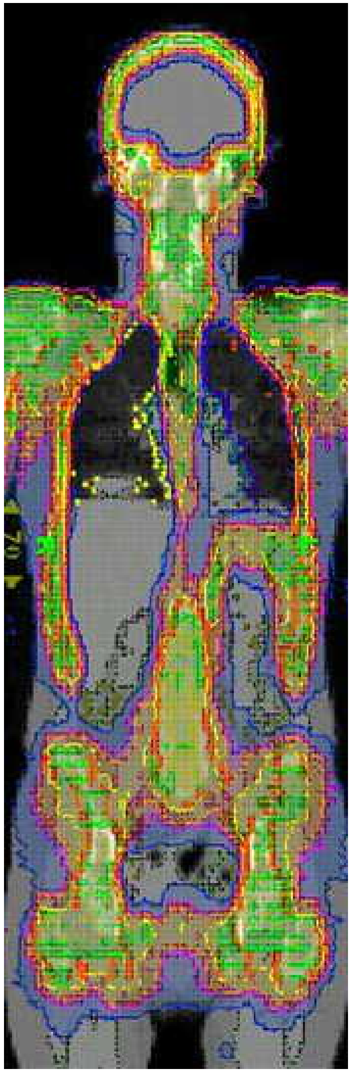
Helical tomotherapy



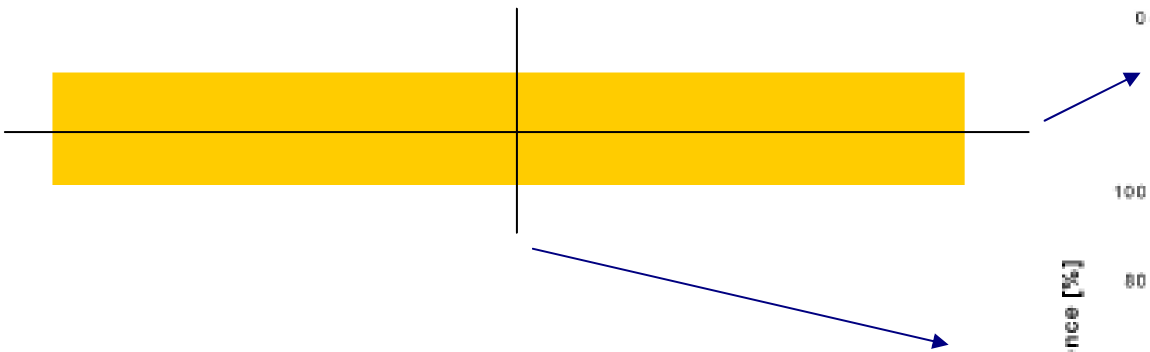


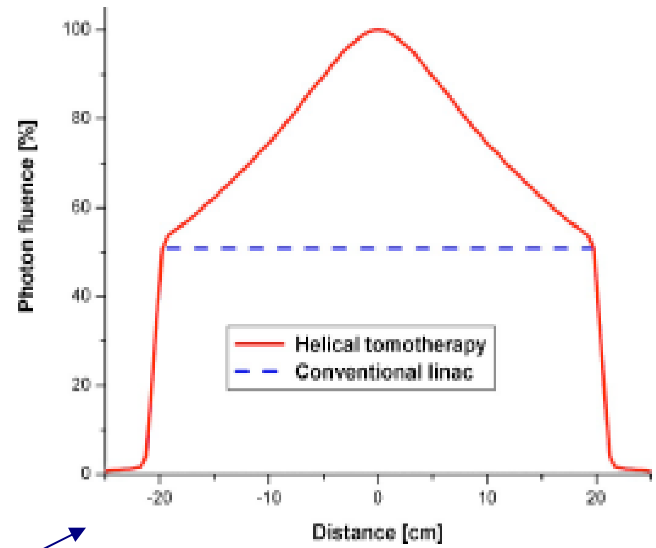
Tomotherapy beam profiles

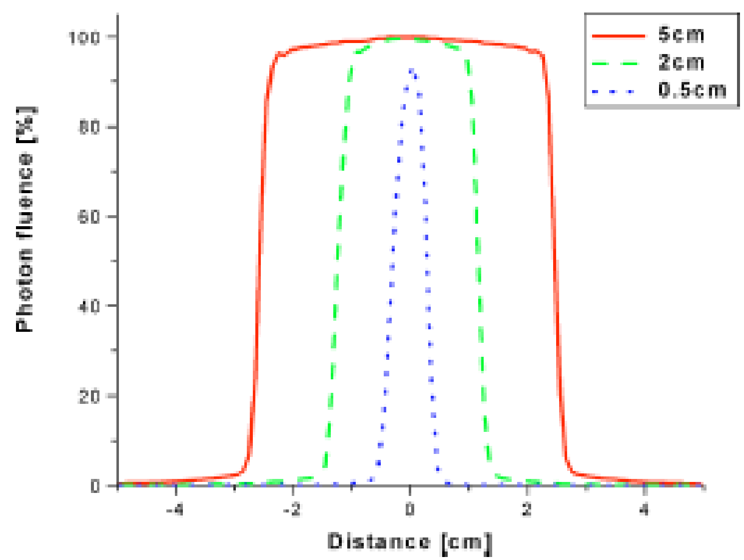
Open field at isocentre:

length: 40 cm

width: 5 cm, 2.5 cm or 1 cm







Jeraj et al., Med Phys 31 (2004) 396-404

Tomotherapy beam collimation

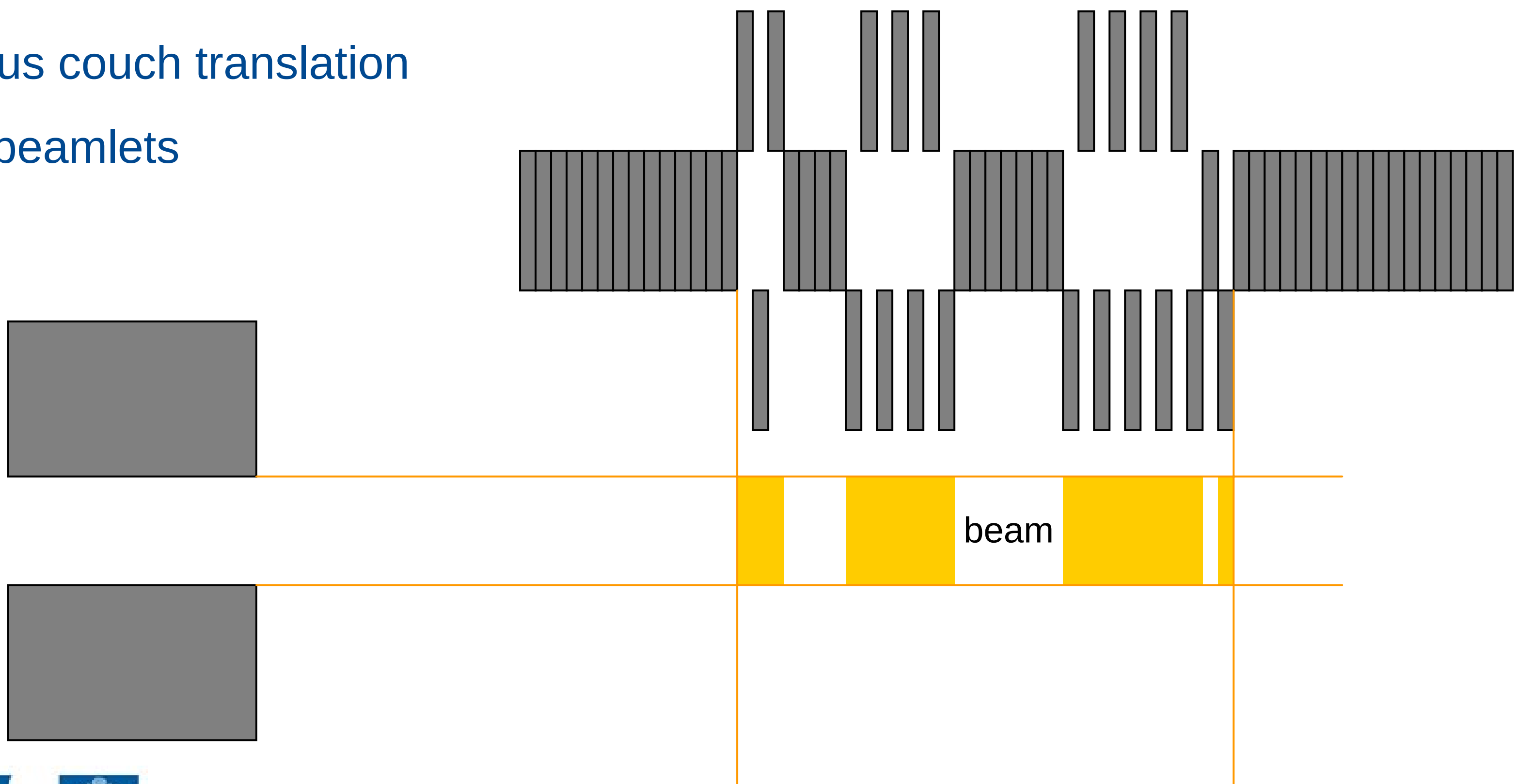
51 gantry angles

64 MLC leaves

Continuous couch translation

… ~ 10^5 beamlets

binary MLC (beam's eye view - displaced)



jaws

(side view)

Dosimetry issues

Max field size is 40 x 5 cm, and field is non-uniform

- Cannot get a 10 cm square, flat field
- None of our dosimetry protocols is directly applicable
  - how to link dose measurements to our familiar absorbed dose standards?
  - we need to restore traceability
- How can the hospital physicist check the doses claimed by the Treatment Planning System?

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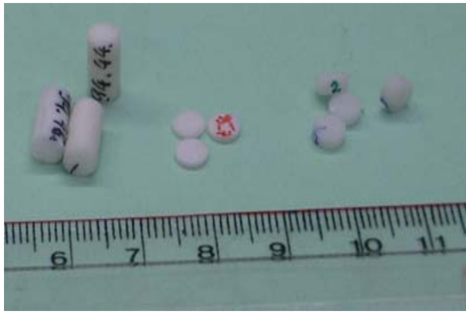
alanine/EPR



advantages

- Pellets are just about sensitive enough for measurements in small therapy-level fields
- Close to water-equivalent (density, atomic no.)
- Response has negligible energy-dependence
- Response is isotropic

drawbacks

- Delayed readout
  - allow 1 day for EPR signal to stabilise
  - results are not available immediately
- Needs an expensive spectrometer for good uncertainty
  - use NPL mailed service!

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Alanine sensitivity

Depends on

- the dosimeter pellet size (mass)
  - In this work, the pellets are ~ 5mm diameter and 2.3 mm thick

  small enough for measurements in tomotherapy beams.

- the EPR spectrometer: standard deviation on dose for one pellet in this work:

  0.06 Gy

Desktop spectrometer may be used, but

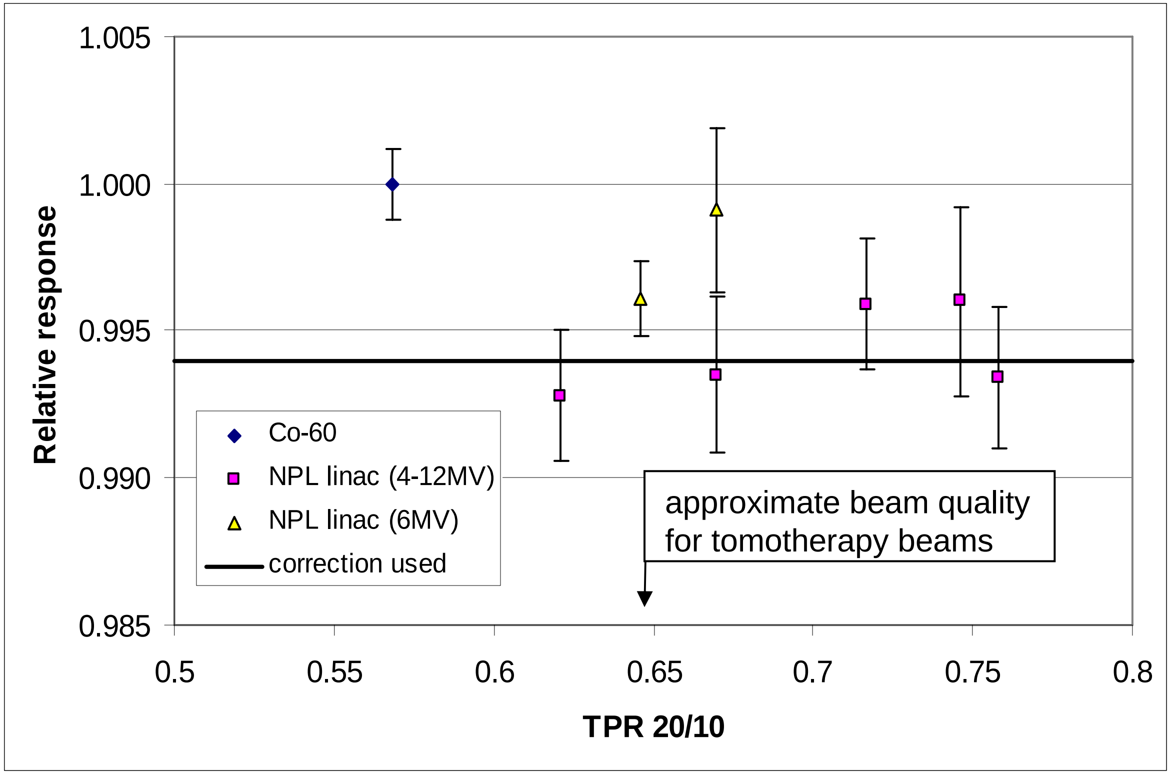
less sensitive ⇨ poorer reproducibility ⇨ worse uncertainty in dose

e.g. 0.3 Gy.

Alanine energy-dependence (seen at NRCC and NPL)

The response of alanine to Co-60 radiation is ~0.6% larger than the response to linac beams.

NPL data:



NPL linac TPRs:

4MV: 0.584, 0.621

6MV: 0.646, 0.670

Uncertainties are 2 sigma

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Outline protocol

- Alanine/EPR sensitivity calibrated at NPL
  - traceable to the same absorbed dose primary standard as our usual NE2611 calibration

- Alanine measurement of absorbed dose in tomotherapy beams
  - Beam size and non-uniformity not a problem
  - Gives machine output

- NE2611 (and field chamber) measurement in same tomo beams
  - Gives cross-calibration

- Measure something like $TPR_{20/10}$ to monitor changes in beam

User can check one chamber against another after NPL has gone

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UK Code of Practice (IPSM, 1990)

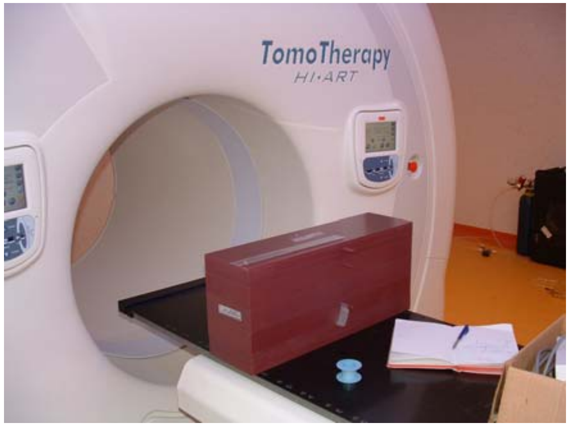
Starting with a calibrated secondary standard $N_{D,w}^{NE2611}(Q)$:

- Beam quality parameter Q is
  - $TPR_{20/10}$ in a 10 x 10 cm beam
- Cross-calibration of field instrument in user beam
  - Interpolate in Q and use a 10 cm square, flat beam, at a depth of 5 cm
- Machine output measurement (Gy per monitor unit)
  - the definition of MU is left to the user …

Our use of alanine has to address all these points

Initial measurements at UCL, Brussels

- Alanine pellets inserted directly in the commissioning phantoms (both homogeneous, solid water), using holes intended for an Exradin A1SL chamber



rectangular phantom (static beam)

cheese phantom (rotating beam)

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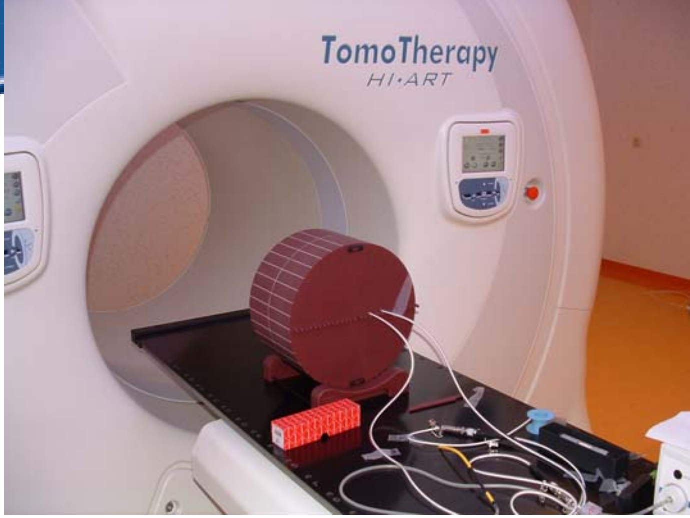
Alanine measurements allow an audit of
A1SL ion chamber dosimetry for a Tomotherapy delivery

Commissioning check – summary



- UCL chambers calibrated at Gent Primary Std lab
  (^{60}Co absorbed dose)

- UCL apply corrections as recommended by TomoTherapy Inc. (i.e. k_Q, k_{ion}, k_{pol})

$k_Q = 0.9965$

$k_{ion} = 1.010$

$k_{pol} = 1.000$

- Agreement to better than 2% in planned target volume

(That's ok.)

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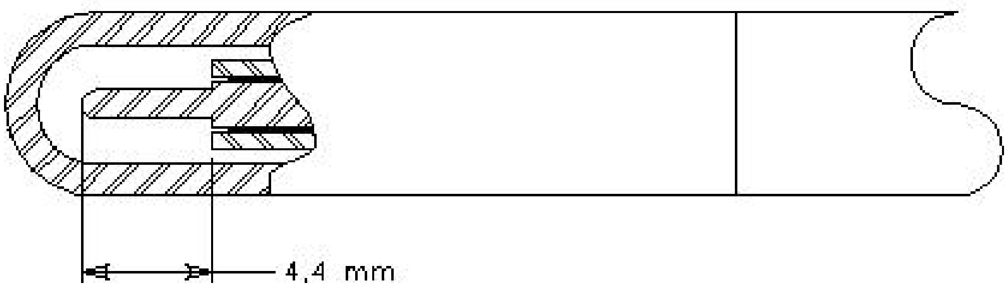
Exradin A1SL ion chamber

- Small volume 0.056 cm^3



- Recommended polarising potential –300V
  - Surely too high.

Summary of data (UCL)

Alanine data are averaged over 2-5 adjacent pellets

Machine/beam	UCL dosimeter	UCL / NPL alanine
Tomo / static 5 cm thick, 1.5 cm deep	A1SL	1.000
Tomo / static 5 cm thick, 5 cm deep	A1SL	1.002
SL25 / 6MV 10x10 cm, 5 cm deep	NE2571	1.002
SL25 / 6MV 10x10 cm, 5 cm deep	NE2571	1.001
Tomo / helical, 2.5 cm thick, in target	A1SL	1.015
Tomo / helical, 2.5 cm thick, in target	A1SL	1.012
Tomo / helical, 1.1 cm thick, in target	A1SL	1.002
Tomo / helical, 1.1 cm thick, in target	A1SL	1.005
Tomo / helical, 5 cm thick, in target	A1SL	1.009
Tomo / helical, 5 cm thick, in target	A1SL	1.011

NB measurements in conventional beams to check consistency in traceability (Gent vs NPL)

Overall, agreement to within 1.5%, with UCL dose greater than NPL dose.

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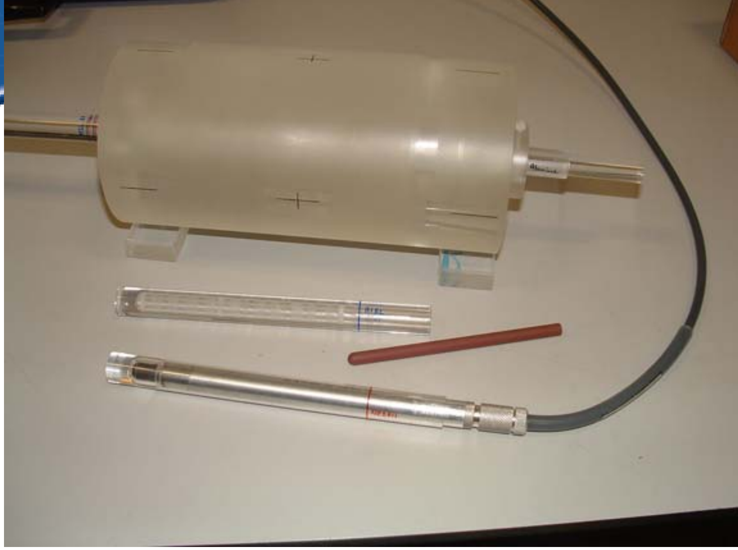
Subsequent measurements (phantom funded by OSL)



- New phantom designed and made at NPL
  - Rexolite (polystyrene)
  - 10 cm diameter x 20 cm length, hole bored on central axis
  - Takes existing 15mm diameter adaptors for
    - NE2611, NE2571 ion chambers
    - alanine in delrin holder (4 pellets)
- also
  - alanine in new Perspex holder (14 pellets)
  - new adaptor for Exradin A1SL chamber

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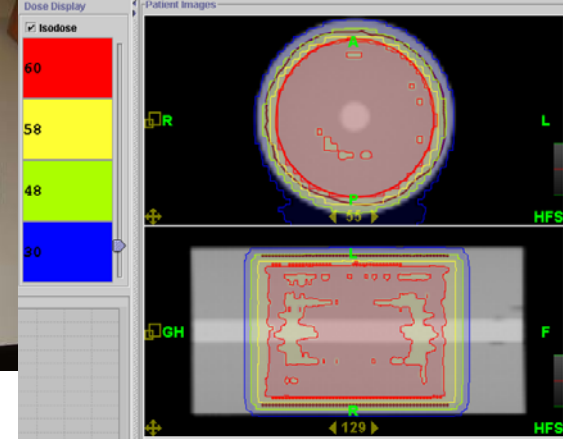
Measurement Protocol



- Hospital makes CT scans of NPL-tomo phantom
- Hospital prepares four helical treatment plans, all with cylindrical target volume, 8 cm diameter x 10 cm long, centred on phantom
  - Phantom concentric with machine
    - 5cm, 2.5cm, 1.1cm thick beam (3 plans)
  - Phantom offset horizontally from isocentre by 13 cm
    - 2.5cm thick beam (1 plan)

  All plans have helical pitch 0.3, rotation time varies with beam thickness
- Irradiations performed in 3Gy fractions
  - Two sets of 14 alanine pellets per plan, 9Gy per set
  - Hospital's secondary standard chamber in each plan (one fraction per reading)
- alanine readout by NPL determines secondary standard calibration
  - Use of alanine contributes 0.1% (type A, reproducibility) plus 0.3% (type B, for Co-60 / MV difference) to calibration uncertainty
  - Combined uncertainty 1.6% (k=2) (c.f. 1.5% for a calibration at NPL)

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$N_{D,w}$ results at Cromwell and NPL

Treatment plan	NE2611/235 ($\times 10^7$ Gy/C)	A1SL/52238 ($\times 10^7$ Gy/C)	Uncertainty (k = 2, 95% CL)
Helical, on-axis, 5cm	10.15	55.95	1.6%
Helical, on-axis, 2.5cm	10.16	55.95	1.6%
Helical, on-axis, 1cm	10.12	55.92	1.6%
Helical, off-axis, 2.5cm	10.18	55.48	3%
Static, 5 x 10 cm	10.15	56.16	1.6%
NPL beam (TPR=0.621)	10.15 (in 2005)	-	1.5%
NPL beam (TPR=0.646)	-	56.35 (in 2006)	1.5%
NPL beam (TPR=0.670)	10.11 (in 2005)	56.46 (in 2006)	1.5%

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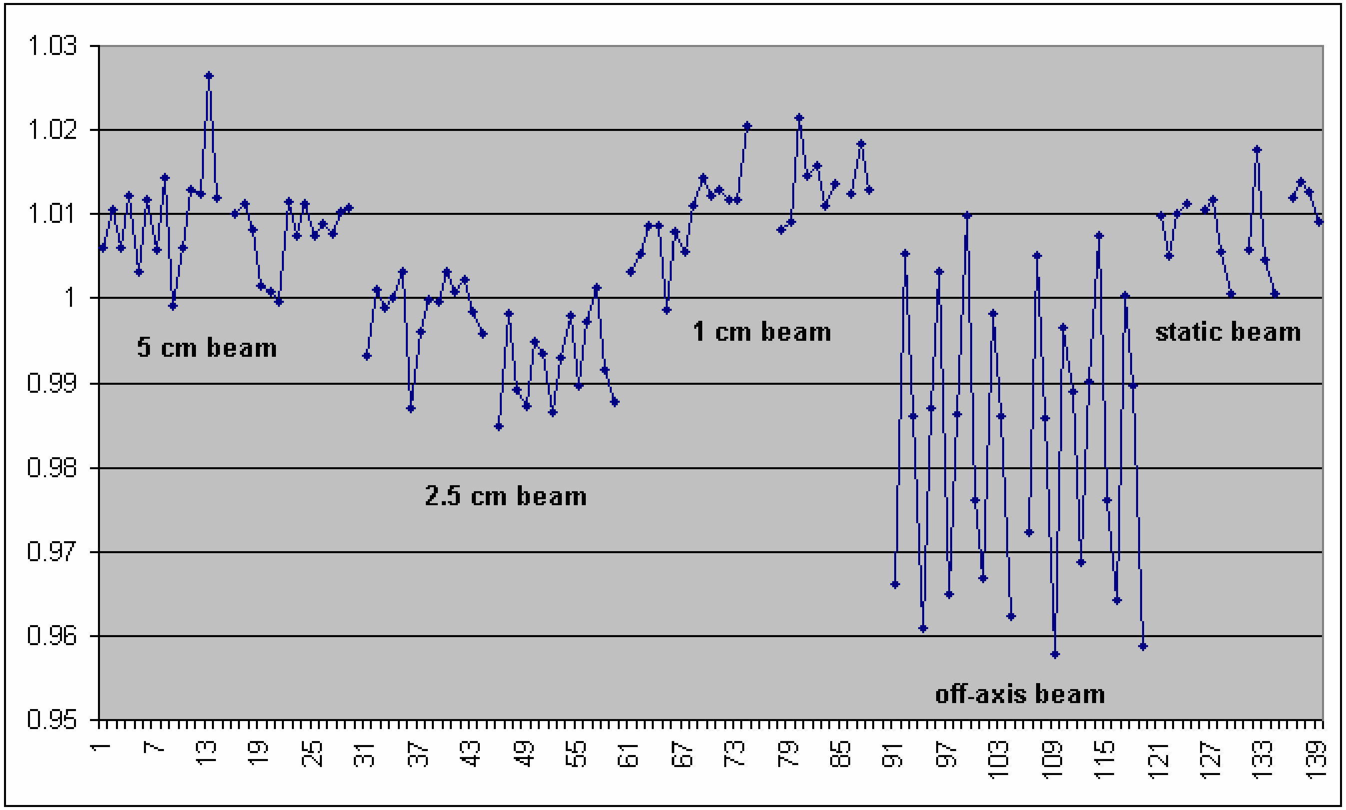
Machine output at Cromwell

Treatment plan	**Dosimeter**	Mean dose / TPS dose and sample std dev
Helical, on-axis, 5cm	60/2017-18 60/2019-20	1.010 ± 0.006 (14) 1.008 ± 0.004 (14)
Helical, on-axis, 2.5cm	60/2025-26 60/2021-22	0.999 ± 0.004 (14) 0.992 ± 0.005 (14)
Helical, on-axis, 1cm	60/2023-24 60/2027-28	1.010 ± 0.005 (14) 1.013 ± 0.004 (10)
Helical, off-axis, 2.5cm	60/2029-30 60/2031-32	0.983 ± 0.017 (14) 0.983 ± 0.017 (14)
Static, 5 x 10 cm	60/2037 60/2038 60/2039 60/2040	1.009 ± 0.003 (4) 1.007 ± 0.005 (4) 1.007 ± 0.007 (4) 1.013 ± 0.002 (4)

Individual pellet doses (Cromwell)

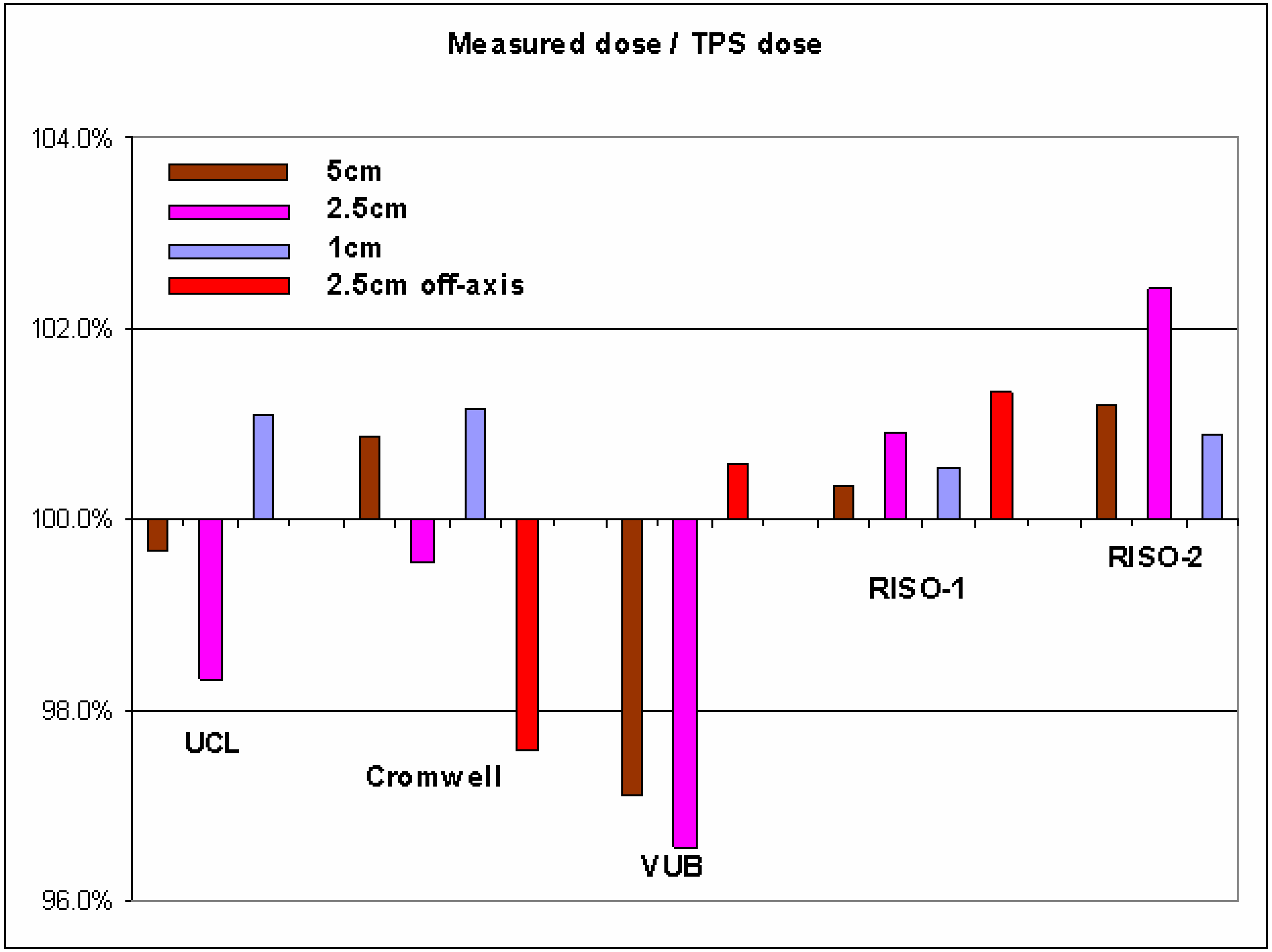
Measured dose / TPS dose

1.0 ± 2%



Measured dose / TPS dose

1.0 ± 2%



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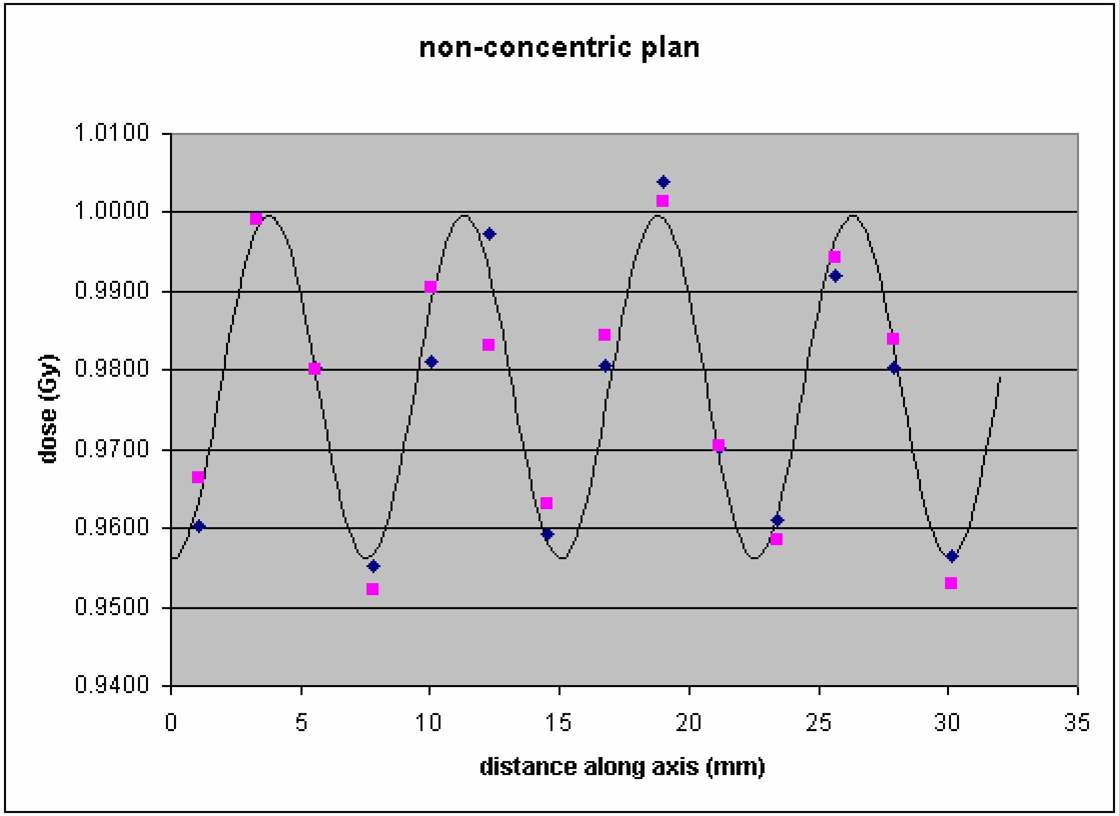
Thread effect (Cromwell Hospital)

- Tomotherapy suggest to use helical pitch = 0.3
  - Couch advances 0.3 x W per gantry rotation, for beam width W
  - “may need smaller value for off-axis treatments”
- Pitch 0.3 used here
  - 4.4% peak-to-peak measured
  - < 1% peak-to-peak according to TPS

Calculation resolution issue?

TPS needs care in use?!



Phantom set up 14 cm off-axis

Planned target volume centred on phantom

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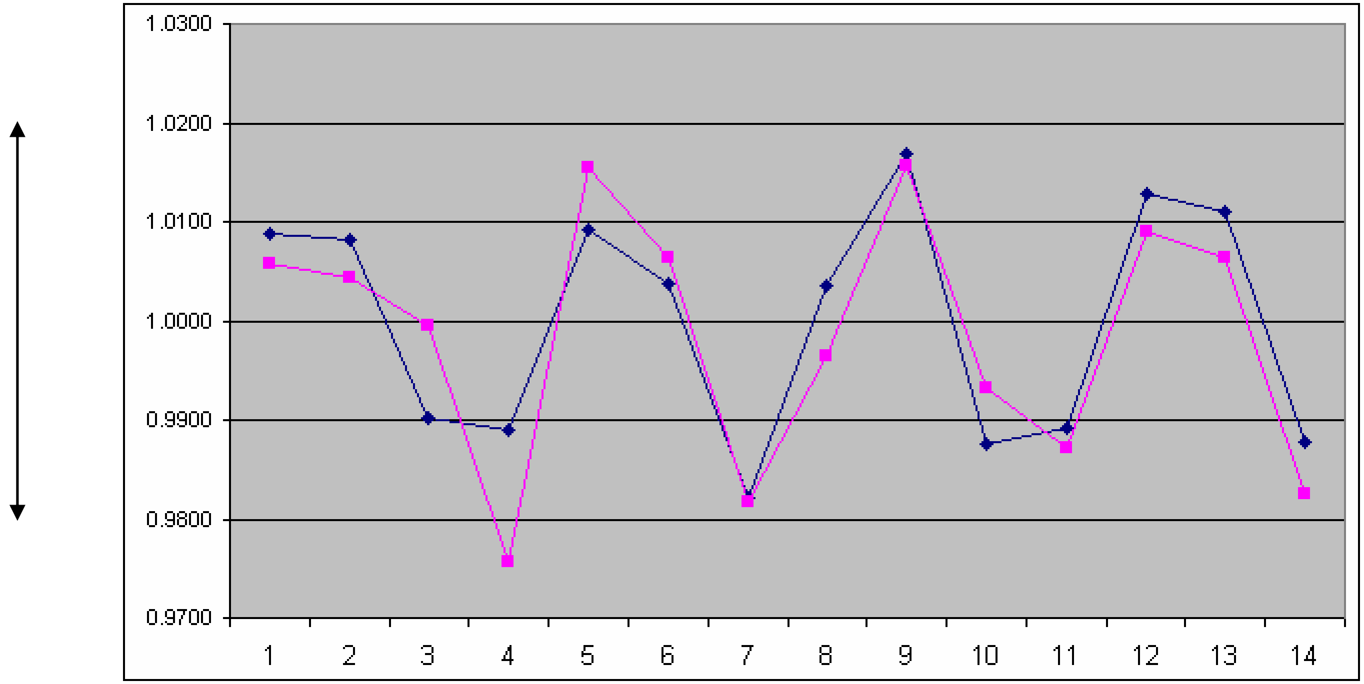
Thread effect (VUB, Brussels)

~4% peak-to-peak



2.5 cm beam, phantom set up 13 cm off-axis

Comparable to Cromwell

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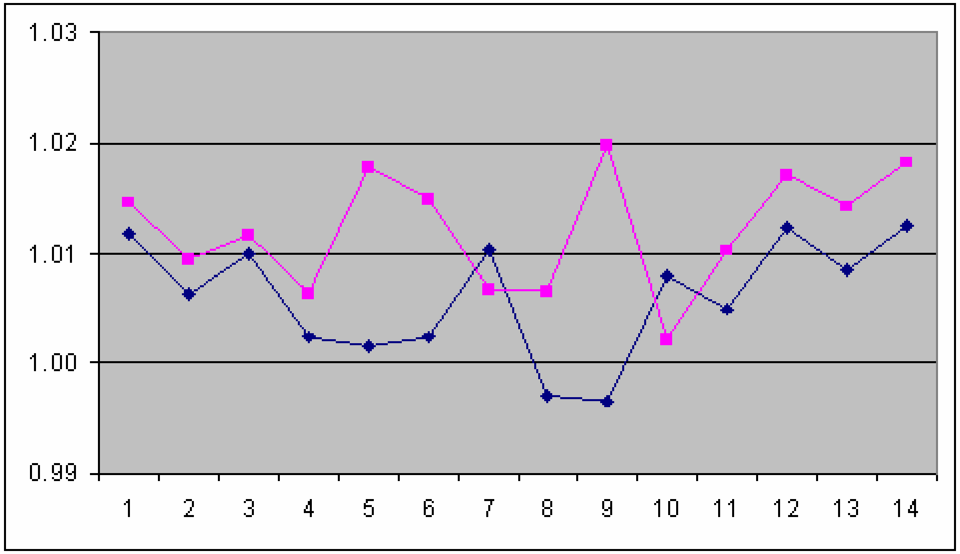
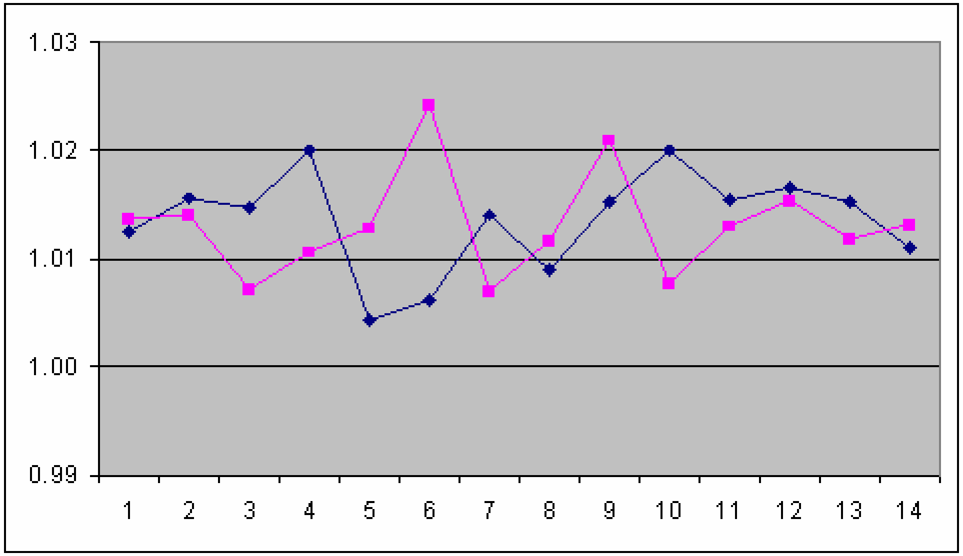
Thread non-effect (RISO, Deventer)

2.5 cm beam, on-axis



2.5 cm beam, off-axis



RISO used pitch = 0.287
instead of 0.300

std dev of pellet doses is 0.5% in each case

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Recombination investigation

- NE2611, NE2571 and A1SL ion chambers
  - four dose rates (static tomo beam, various depths and distances)
  - many polarising voltages
  - initial and volume recombination separated
  - charge multiplication seen
    - A1SL above –100V (-300V is recommended)
    - NE2571 at –400V (-250V is recommended)
    - not seen in NE2611

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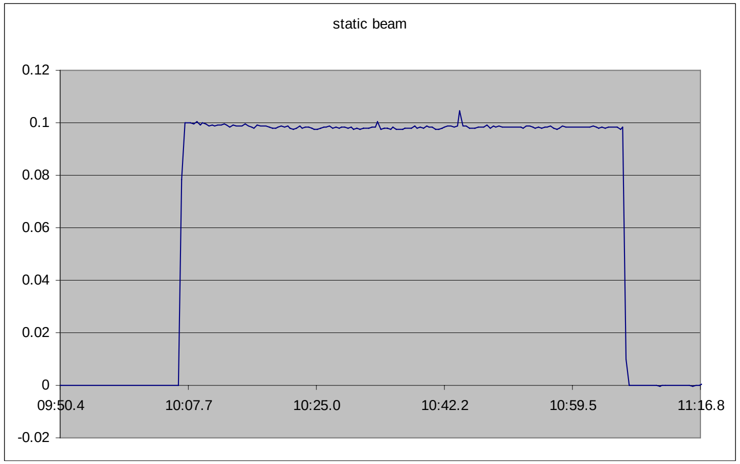
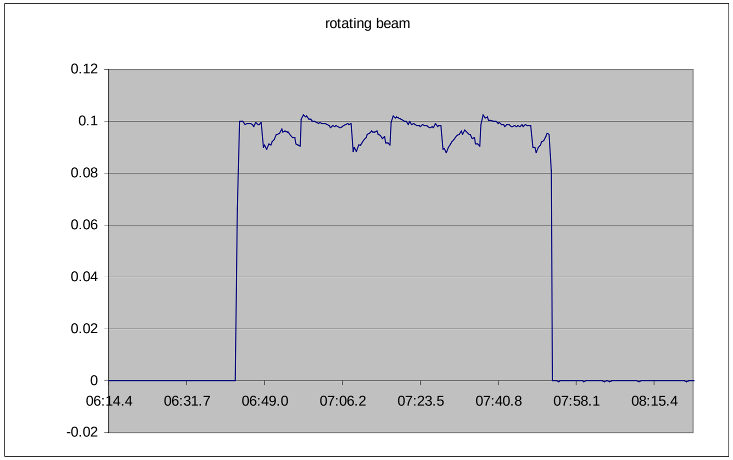
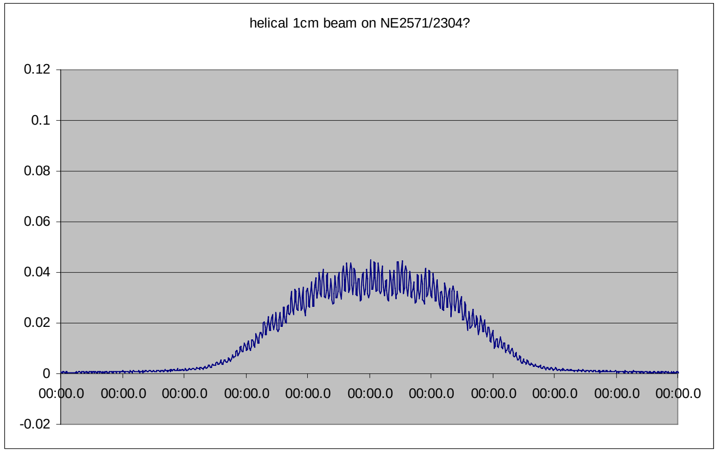
Dose per pulse and beam modulation



Static beam



Rotating beam



Helical beam

Ion recombination – summary of results

- NE2611 chamber
  - Saturation measurements in tomo beams at Cromwell give

    k_{ion} = 1.009

  consistent with expectations: $k_{ion} = 1 + a + b\,D_p$

though dose per pulse D_p may not be what you expect.

- A1SL chamber
  - Saturation measurements in tomo beams at Cromwell give

    k_{ion} = 1.001 to 1.002

  depending on position in phantom, consistent with theory

Much less than the k_{ion} = 1.01 recommended by TomoTherapy Inc

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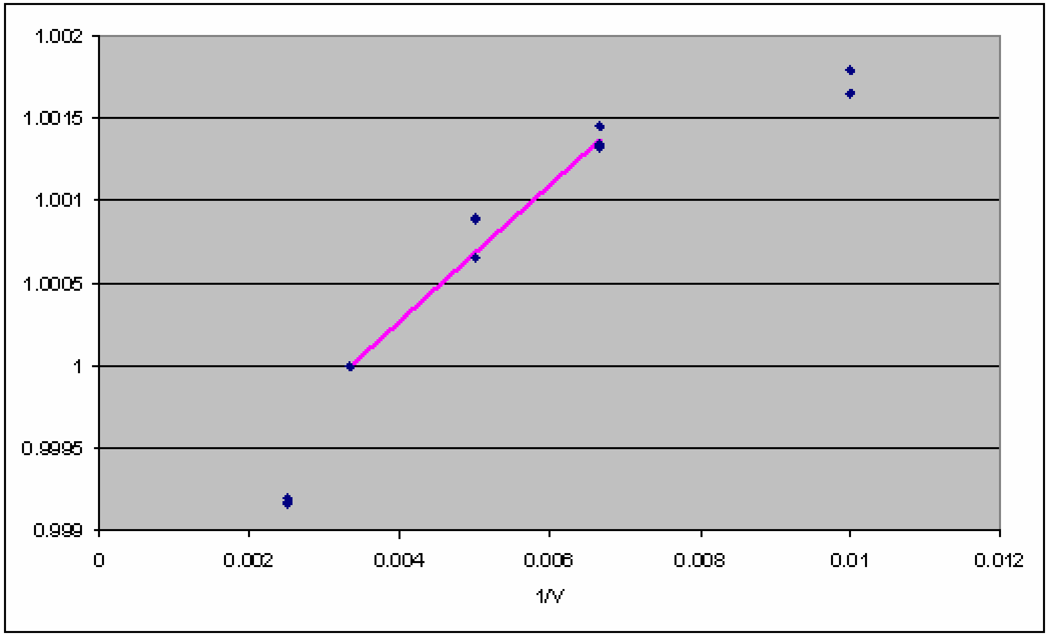
Charge multiplication in the A1SL

- A1SL measurements in Co-60
- using V = -400, -300, -200, -150, -100



- For this chamber, V = -300 and V/2 = -150 are clearly in the range where charge multiplication is happening. The correction for ion recombination is more complicated…

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Conclusions

Hospital physicists in Europe are less ready than those in North America to take the manufacturer's dosimetry at face value (to use the system as a "black box")

- The manufacturer's dosimetry in their TomoTherapy machines is ok:
  - NPL alanine dosimetry agrees with TPS within 2% at Cromwell
  - Alanine and ion chamber dosimetry agree within 1.5% at UCL
  - Tomo 1 and Tomo 2 at RISO agree (after a 1% adjustment of Tomo 2)

- 1.01 correction for ion recombination in A1SL chamber is too large
  - NPL measurements indicate 1.001 to 1.002 (depending on position in phantom)
  - Correction for an NE2611 is 1.009 (for these measurements)

- pitch = 0.287 is much better than pitch = 0.300 (thread effect)

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Current and Future work

- NPL offers alanine measurements in the NPL-tomo phantom as a routine service to any TomoTherapy user, with
  - on-site measurements by NPL for UK users
  - Postal service (phantom and dosimeters) for non-UK users

- TomoTherapy Inc propose a similar use of NPL alanine to check their commissioning of new machines.

Acknowledgements

Thanks to

- TomoTherapy users for permission to use their results
  - Vincent Althof et al. (RISO, Deventer)
  - Dirk Verellen et al. (VUB, Brussels)
  - David Nicholas (Cromwell, London)
- OSL for funding
  - Design and manufacture of NPL-tomo phantom
  - NPL measurements at Cromwell Hospital

- UK Government DTI funded the rest of NPL's work, as part of a dosimetry in small fields and for IMRT.

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General questions

- In this work we only specified the dose distribution, and let the TPS determine the treatment (i.e. decide how to set up the MLC).
  - Proper reference conditions are not so ambiguous!
  - Could we define clinically relevant “reference” conditions?
- Is the resulting chamber calibration applicable to other treatments?
  - Arguably a helical beam is at least more relevant than a static beam.
- Do we need a primary standard more suited to IMRT?

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Thank you!