A practical approach to

Dosimetry and Quality Assurance

International Conference on Medical Accelerators and Particle Therapy

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DOSIMETRY

Outline

Dosimetry	**&**	**Quality Assurance**
Absolute Dosimetry		**Commissioning**
Relative Dosimetry		**Machine QA**
		Patient QA

Dosimetry

Absolute Dosimetry

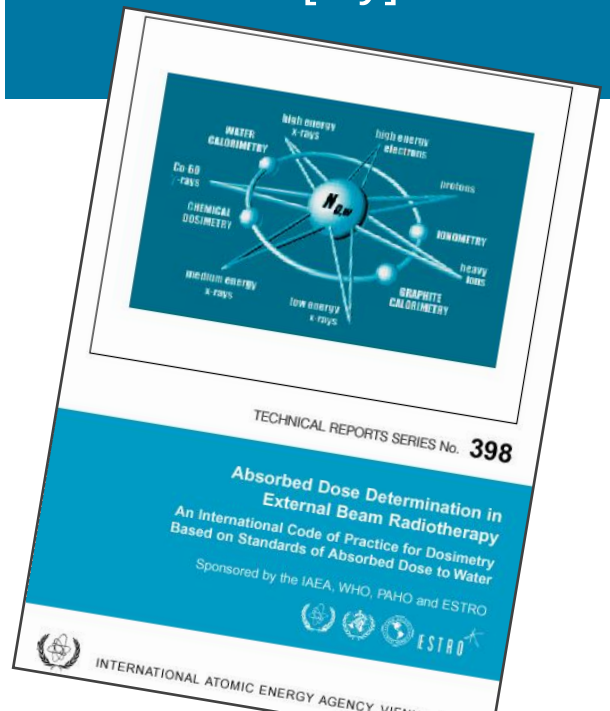
What is physical dose in a given point?
[Gy]

Absolute Dosimetry

Dosimetry

Absolute Dosimetry

What is physical dose in a given point?
[Gy]



- International dosimetric code of practice for absolute dosimetry:
  IAEA TRS-398 (2006)
- Quantify of interest :
  Absorbed dose to water
  = energy deposited in a medium by ionizing radiation per unit mass [Gy]
- TRS-398 focused on scattering delivery (2006)
- Common detectors:

Primary Standard		Clinical Standard
Calorimeters	Faraday Cups	Ionization Chambers

Plan

Dosimetry

Absolute Dosimetry

What is physical dose in a given point?
[Gy]

Primary Standard

Clinical Standard

Calorimeters

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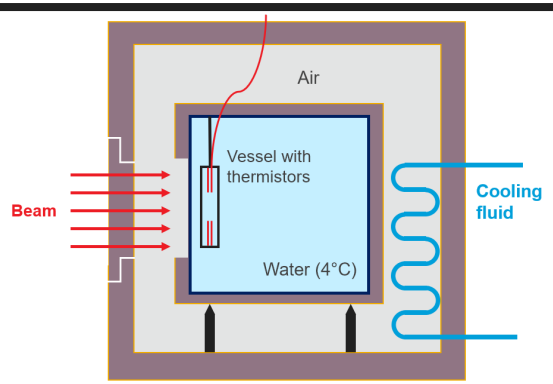
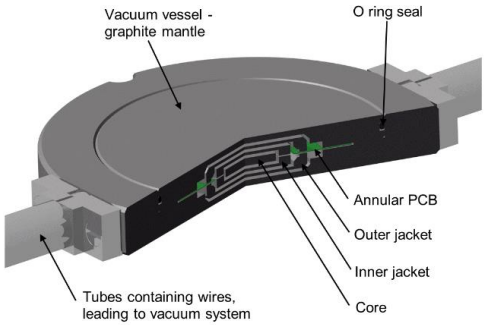
Ionization Chambers

Calorimeters

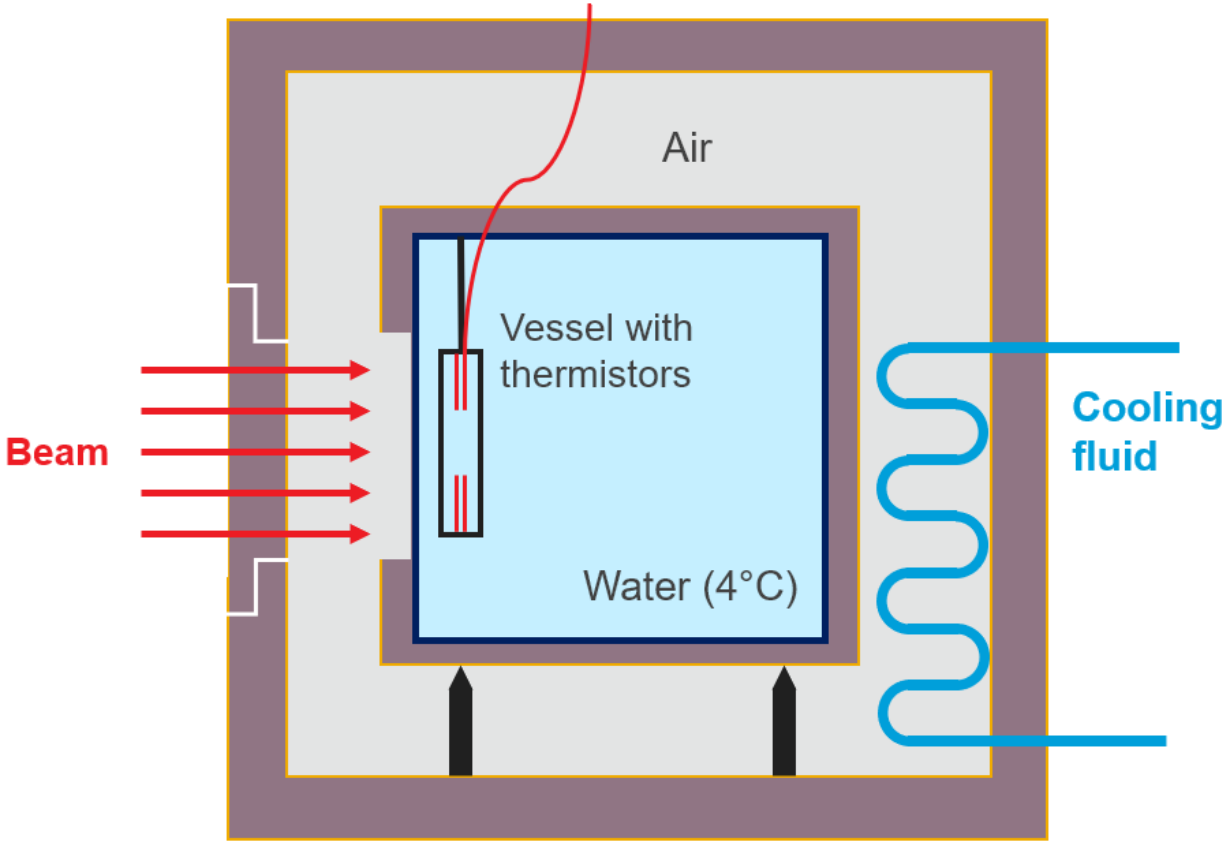
Calorimeter: Measure of the temperature rise in a medium due to energy absorbed from the radiation beam

$$D_m = c_{p,m} \Delta T \, k_i$$

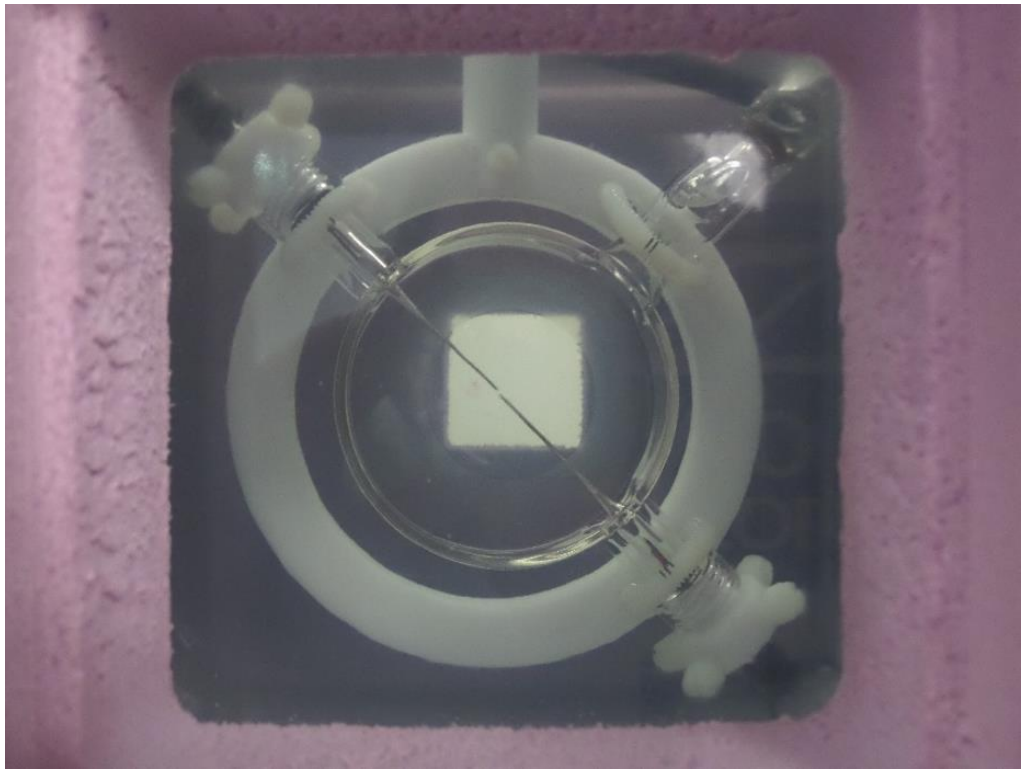
c_p : specific heat capacity
ΔT: temperature rise
k_i: correction factors

	$\Delta T / D_m$	+ Pros & - Cons	Illustration	References
Water	0.24 mK/Gy	+ Dose in Water - Cumbersome setup - Lower sensitivity		• Sarfehnia et al. (2010) Med Phys 37(7) 3541 • Renaud et al. (2016) Phys Med Biol 61(18) 6602 • Medin et al. (2010) Phys Med Biol 55(12) 3287
Graphite	1.41 mK/Gy	- Dose conversion + More portable + Higher sensitivity		• Palmans et al. (2004) Phys Med Biol 49(16) 3737

Water Calorimeter



Water Calorimeter



Vessel with thermistors

Courtesy of Séverine Rossomme

Faraday cup

- **Faraday cup :** shielded insulated block which stops the beam and measure the accumulated charge

Pyramid BC-75

$$D_m = \phi \left(\frac{S}{\rho}\right)_m = \frac{N}{A}\left(\frac{S}{\rho}\right)_m$$

ϕ : fluence
A : the effective beam area
N : number of protons collected by the cup
$\left(\frac{S}{\rho}\right)_m$ = mass stopping power

+ Portable
- Complex design to guarantee accuracy
- Depends on energy spectrum and stopping power

Cambria *et al.* (1997) Phys Med Biol 42, 1185

Ionization chamber

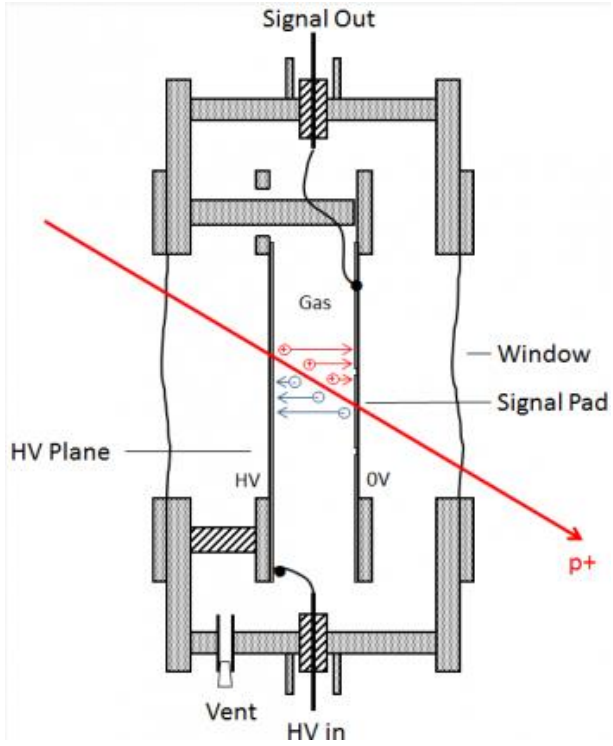
- **Ionization chamber**: measure of charges created due to radiation beam and collected on the electrodes

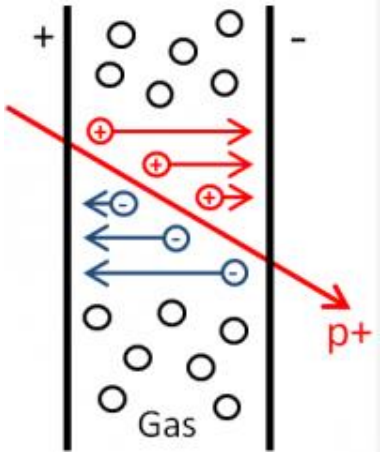
$$D_{w,Q} = M_Q \, N_{D,w,Q_0} k_{Q,Q_0}$$

M_Q: corrected response of the ionization chamber for
- temperature and pressure (k_{TP})
- recombination (k_s)
- polarity (k_{pol})

N_{D,w,Q_0}: calibration factor in terms of absorbed dose to water

k_{Q,Q_0}: correction factor for the radiation quality of the beam





k_Q (TRS-398)

TABLE 10.III. CALCULATED VALUES OF k_Q FOR PROTON BEAMS, FOR VARIOUS CYLINDRICAL AND PLANE-PARALLEL IONIZATION CHAMBERS AS A FUNCTION OF BEAM QUALITY R_{res}

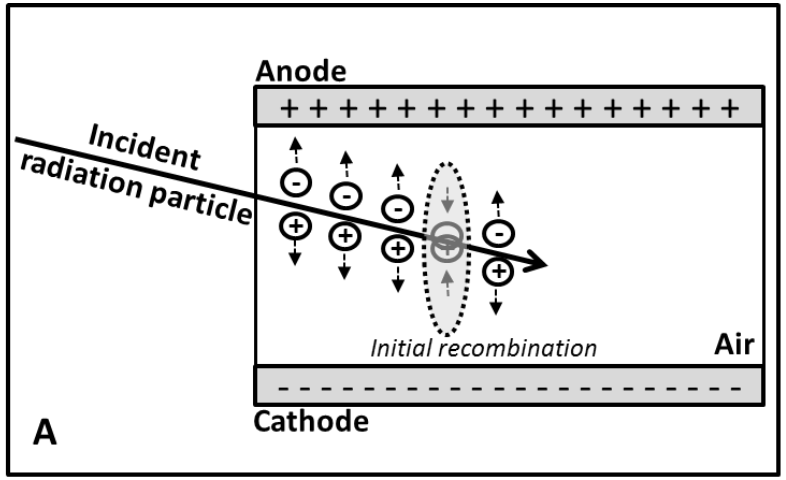
Ionization chamber type [a]	Beam quality R_{res} (g cm^{-2})															
	0.25	0.5	1	1.5	2	2.5	3	3.5	4	4.5	5	7.5	10	15	20	30
Markus	1.009	1.005	1.004	1.003	1.003	1.003	1.003	1.003	1.002	1.002	1.00					

k_s ion recombination correction factor

Initial recombination

Ions created in the same ionization track

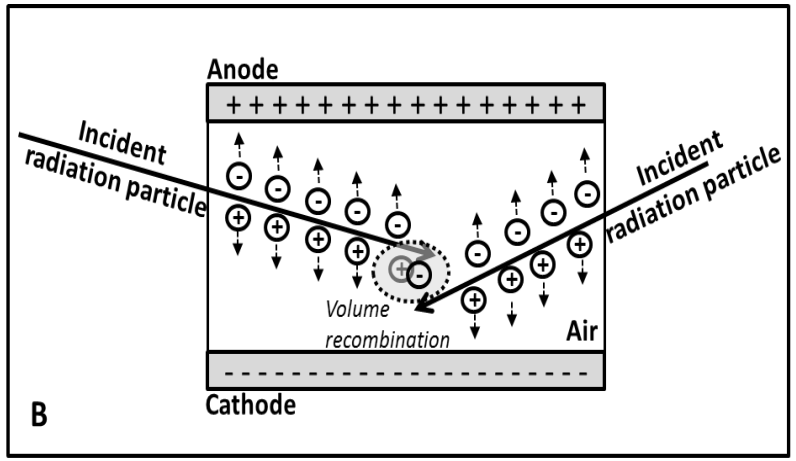
- Independent on the ionization current
- Theories: Jaffé, Onsager



Volume recombination:

Ions created in different ionization tracks

- dependent on the ionization current, thus the dose rate
- Theorie: Boag



Protons: total recombination is dominated by volume recombination but initial recombination cannot be neglected

Kanai *et al.* (1998) Phys Med Biol 43(12):3549
Rossomme *et al.* (2016) Med Phys 43(7):4198

Today's Challenges: high dose rates

Boag formula (1er order simplification for pulsed beam)

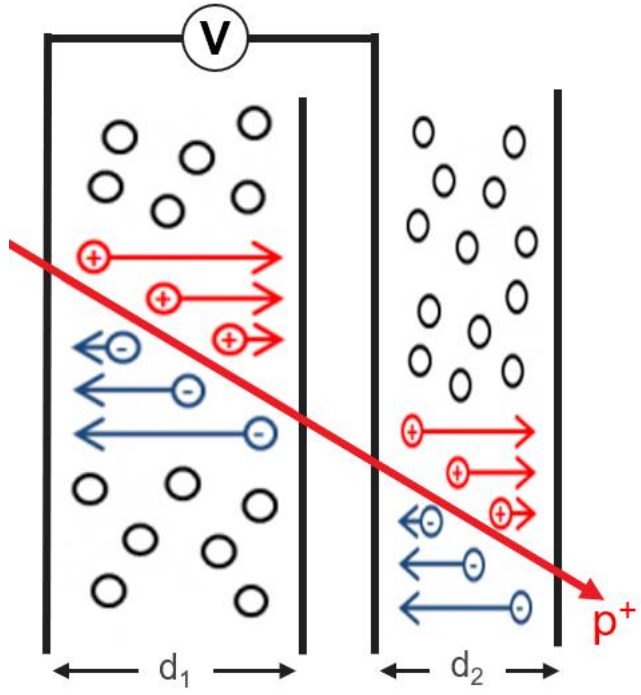
$$k_s^{vol,pulsed} = 1 + \frac{m\ d\ I_{sat}}{V}$$

m: depends on the ion recombination coefficient and mobility of the ions in the gas

I_{sat}: saturation current

How to deal with recombination?

- Increase High voltage (V)
  Limitations: avalanche effect, manufacturing ,etc
- Reduce Gap (d)
  Limitations: low signal, manufacturing, etc
- Change gas (m)
- Asymmetrical IC
- …



Asymmetrical IC

Prieels et al, PTCOG2011, Philadelphia

Plan

Dosimetry

Absolute Dosimetry

What is physical dose in a given point?
[Gy]

Primary Standard

Clinical Standard

Calorimeters

Faraday Cups

Ionization Chambers

Relative Dosimetry

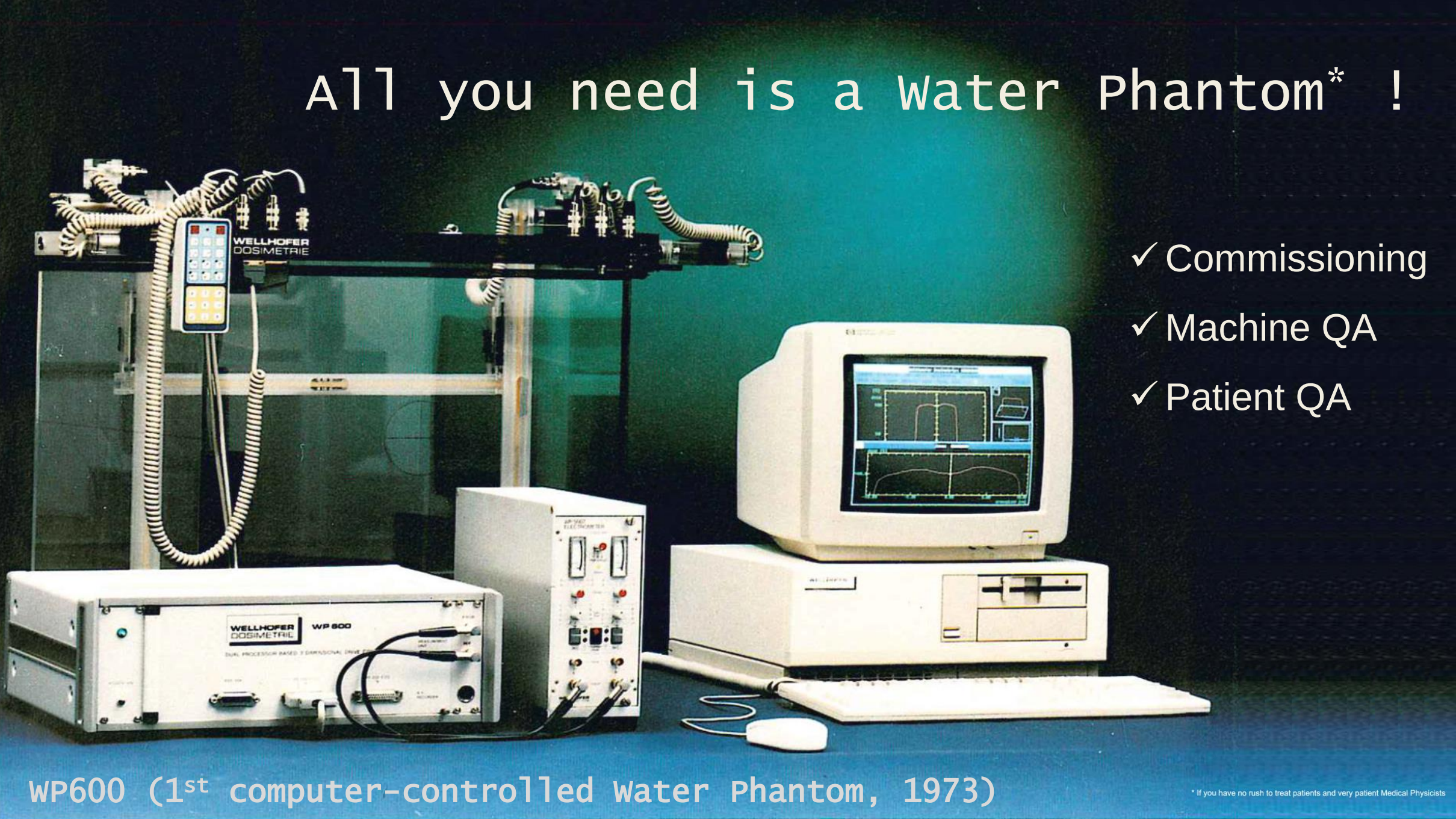
How dose in a given point compares to another?
[%]

Depth Dose

Lateral Dose

Water Phantom
+
Ionization Chamber
Diode
…

All you need is a Water Phantom* !



- ✓ Commissioning
- ✓ Machine QA
- ✓ Patient QA

WP600 (1st computer-controlled Water Phantom, 1973)

* If you have no rush to treat patients and very patient Medical Physicists

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How dose in a given point compares to another?
[%]

Depth Dose

Lateral Dose

Water Phantom with Ionization Chamber, diode,…)

Main challenge

Dosimetry

Quality Assurance

Commissioning	More efficiency
Machine QA	More efficiency
Patient QA	More efficiency

More affordable Proton Therapy

Dosimetry

Quality Assurance

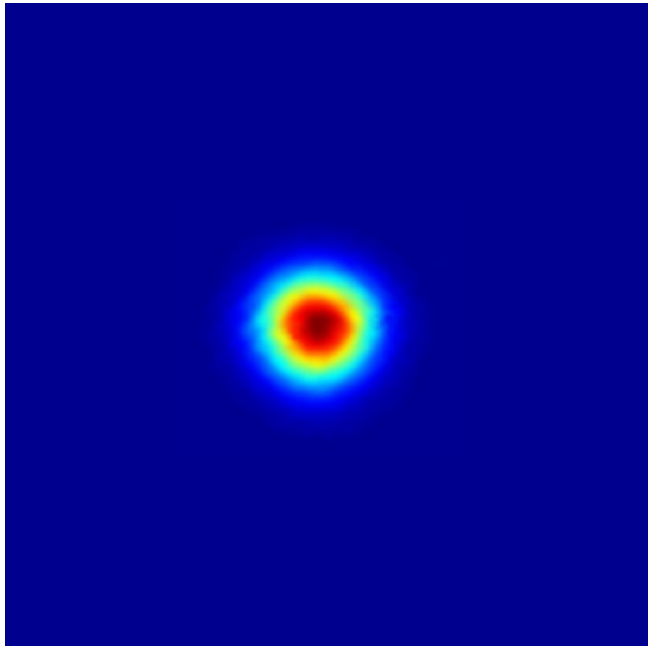
Commissioning

Machine QA

Patient QA

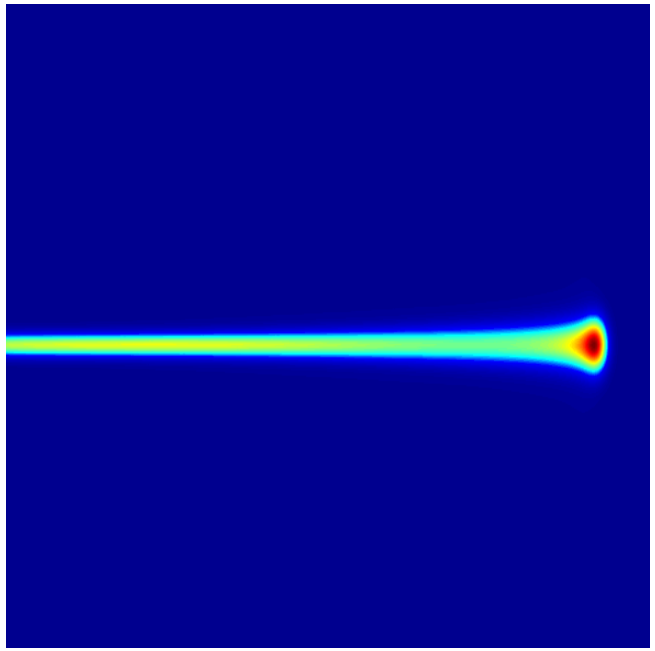
PBS is very simple

It is just a combination of:



Spots

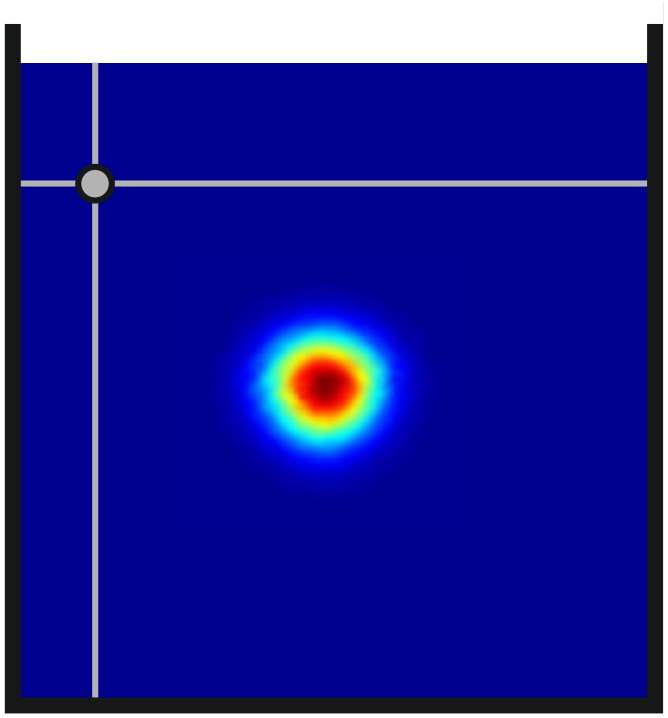
&



Bragg Peaks

Both can easily be measured by a Water Phantom

Spot Measurement



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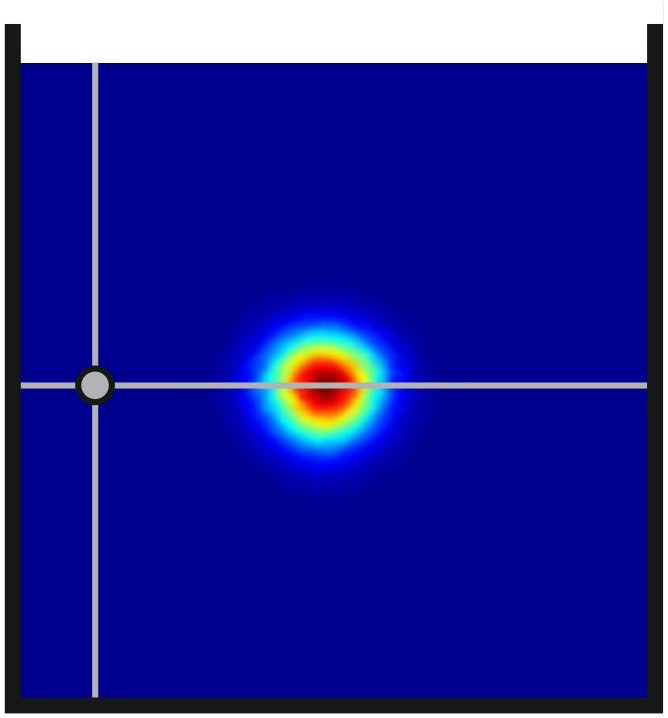

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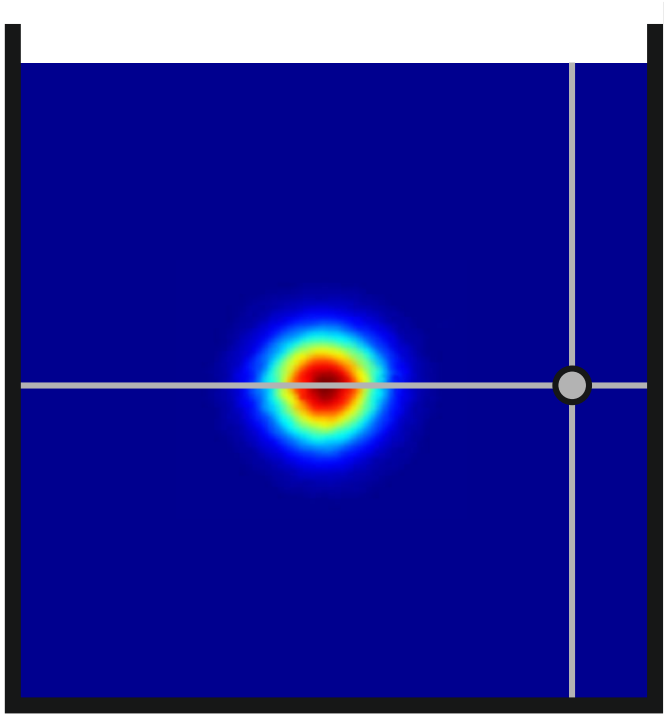
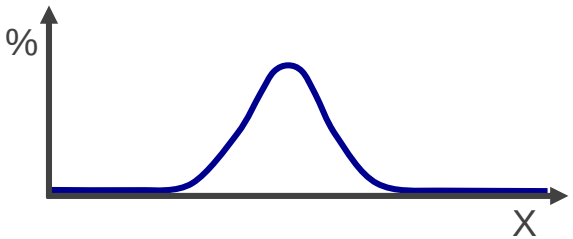
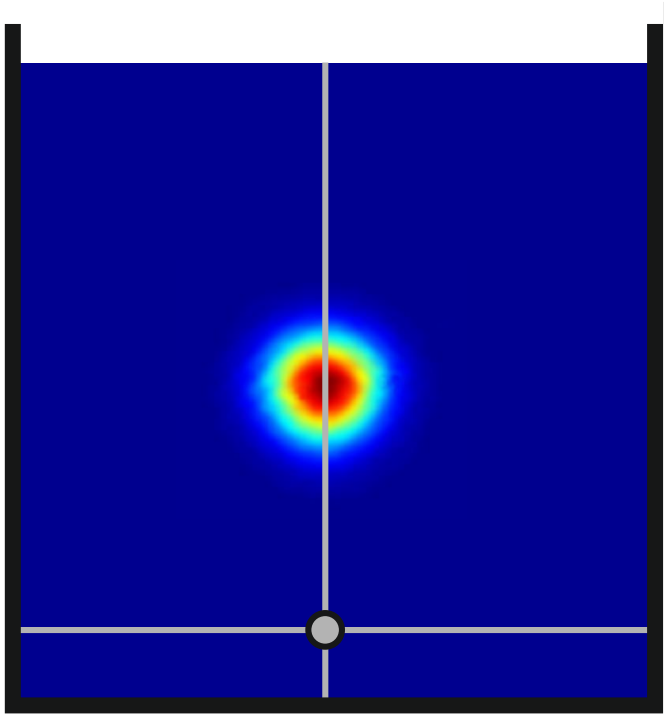
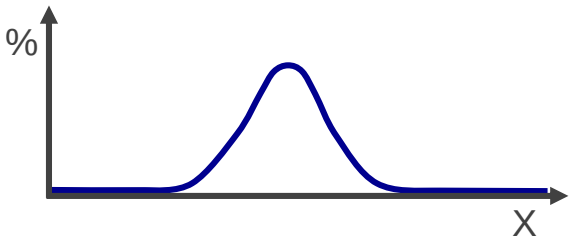




Measurement	Time
X	≃ 45 s

Spot Measurement





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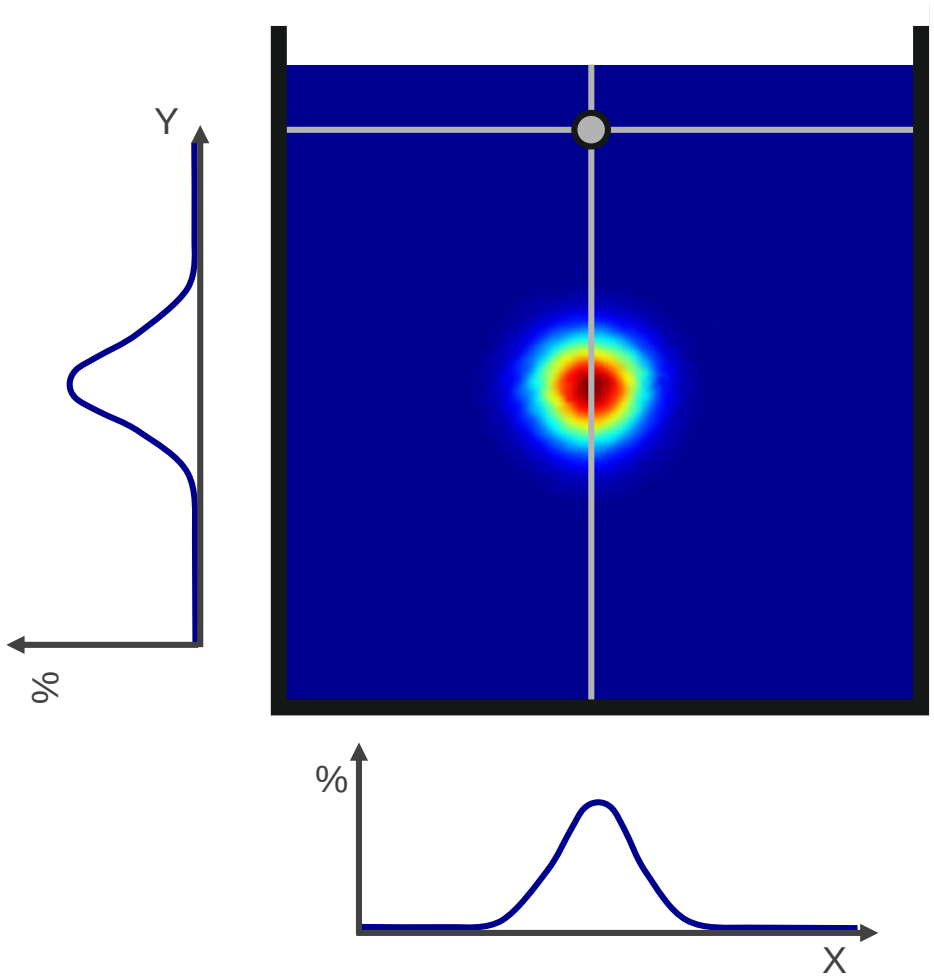
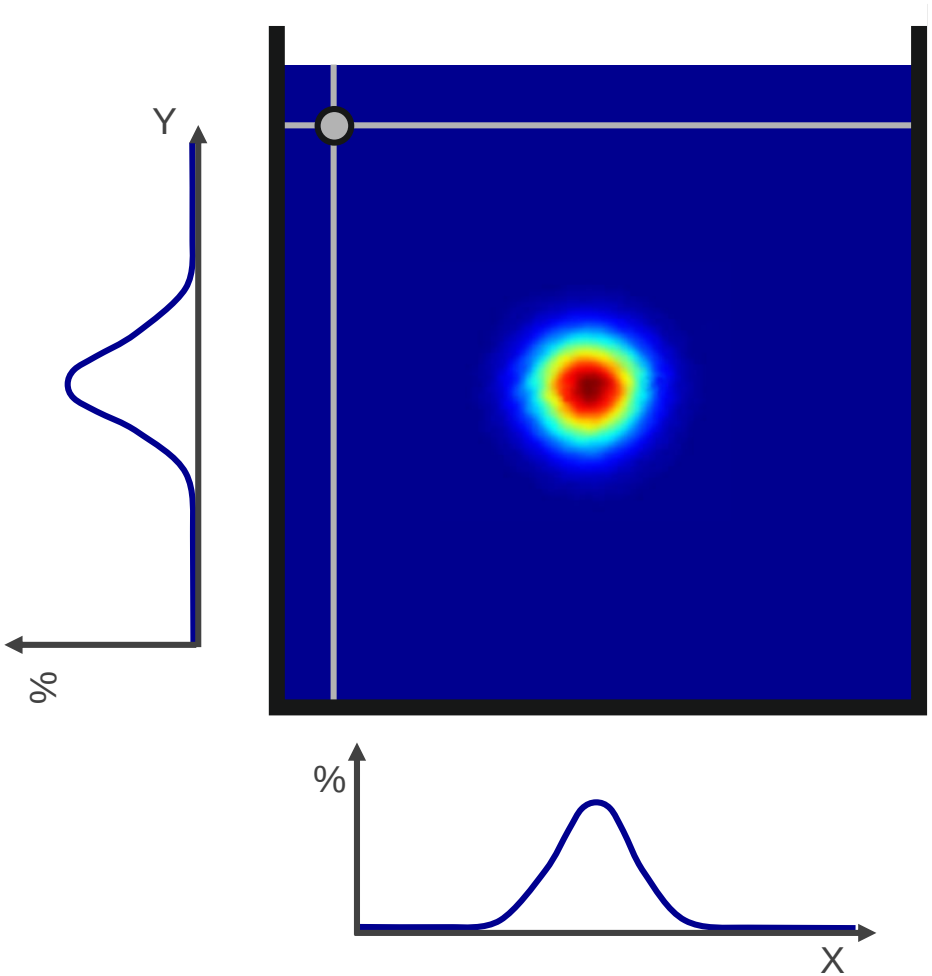


Measurement	Time
X	≃ 45 s
Y	≃ 45 s

Spot Measurement



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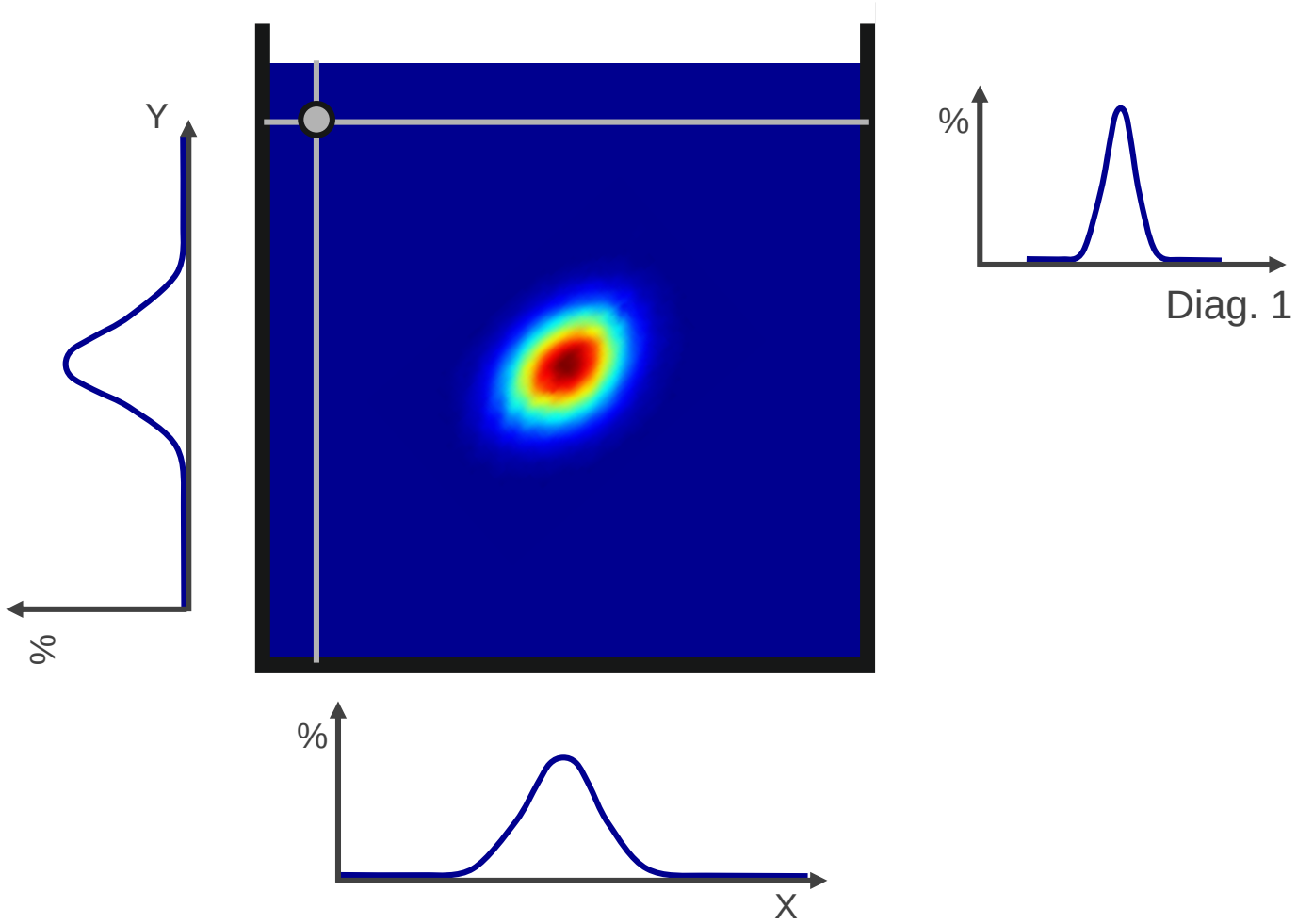
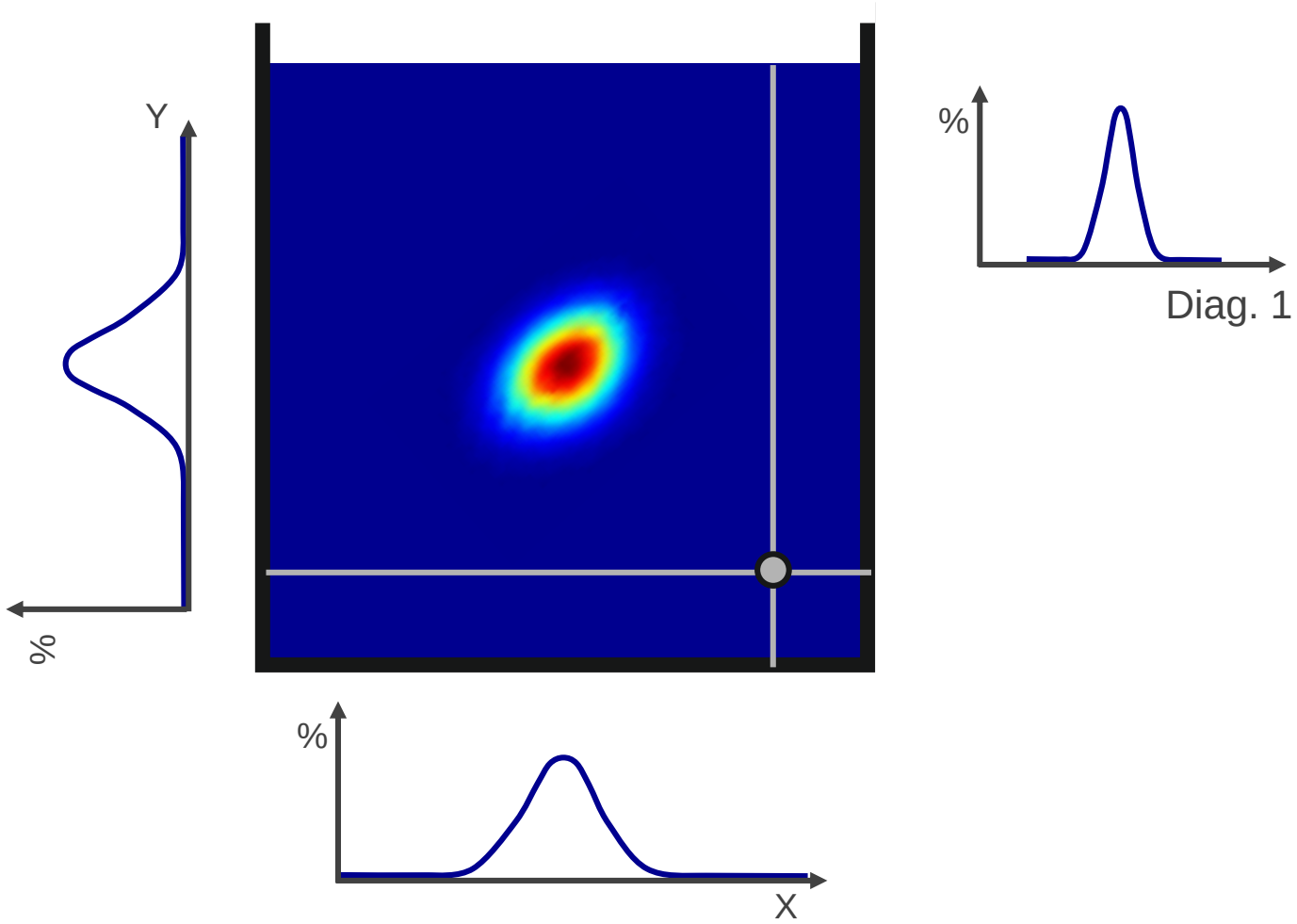


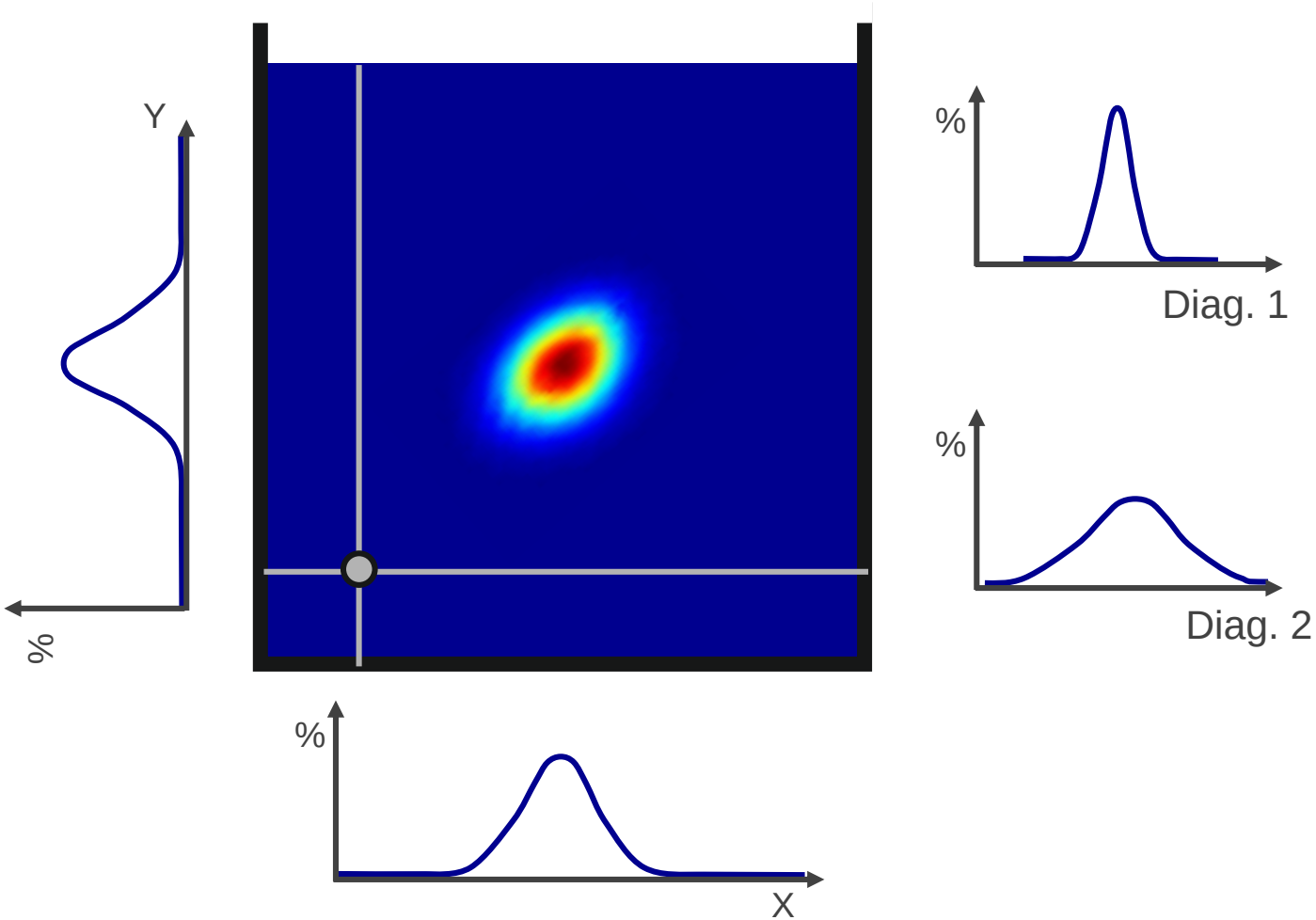
Measurement	Time
X	≃ 45 s
Y	≃ 45 s
Diagonal 1	≃ 45 s

Spot Measurement



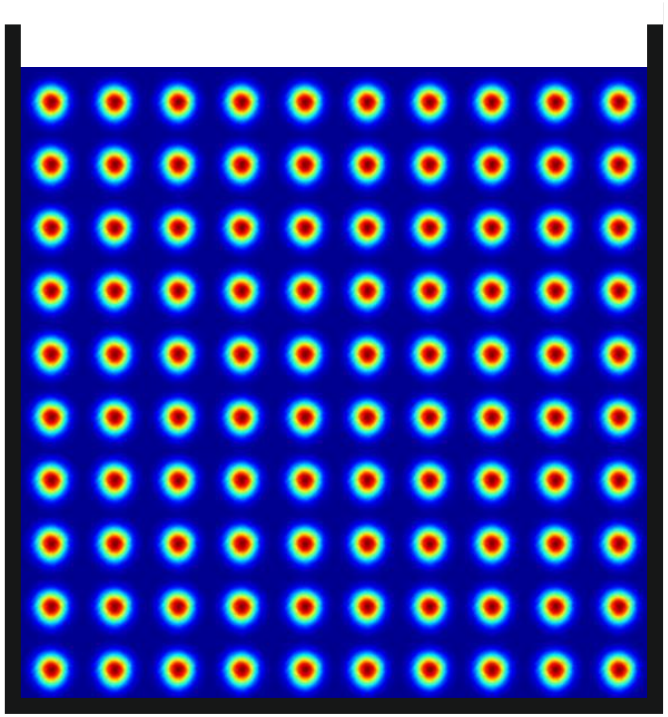
Measurement	Time
X	≃ 45 s
Y	≃ 45 s
Diagonal 1	≃ 45 s

Spot Measurement



Measurement	Time
X	≃ 45 s
Y	≃ 45 s
Diagonal 1	≃ 45 s
Diagonal 2	≃ 45 s
Total per Spot	***≃ 3 min/spot***

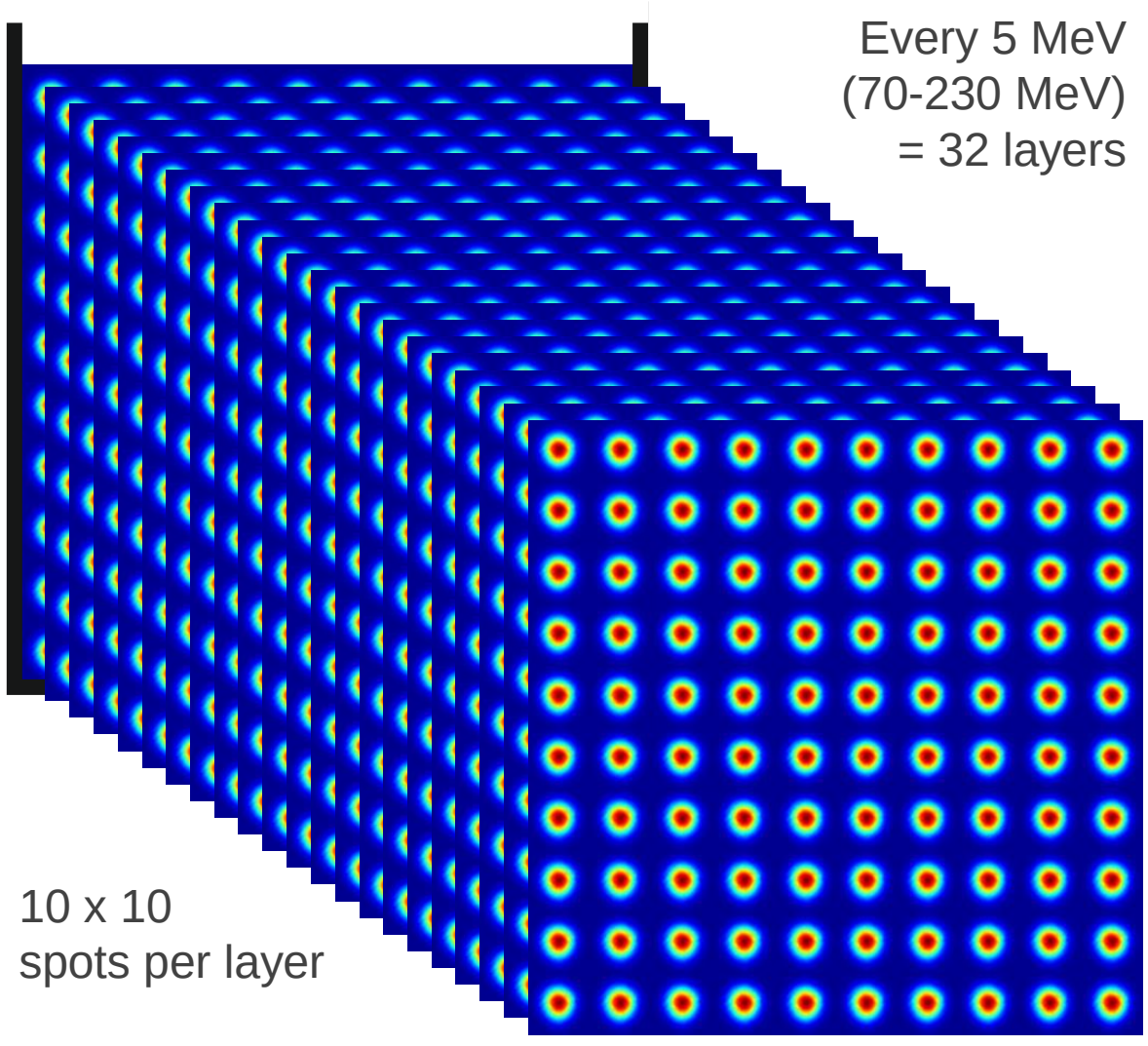
Tilted Spot Measurement



10 x 10
spots

Measurement	Time
X	≃ 45 s
Y	≃ 45 s
Diagonal 1	≃ 45 s
Diagonal 2	≃ 45 s
Total per Spot	*≃ 3 min/spot*
Layer (100 spots)	≃ 300 min/layer
	≃ 5 h/layer

Tilted Spot Measurement



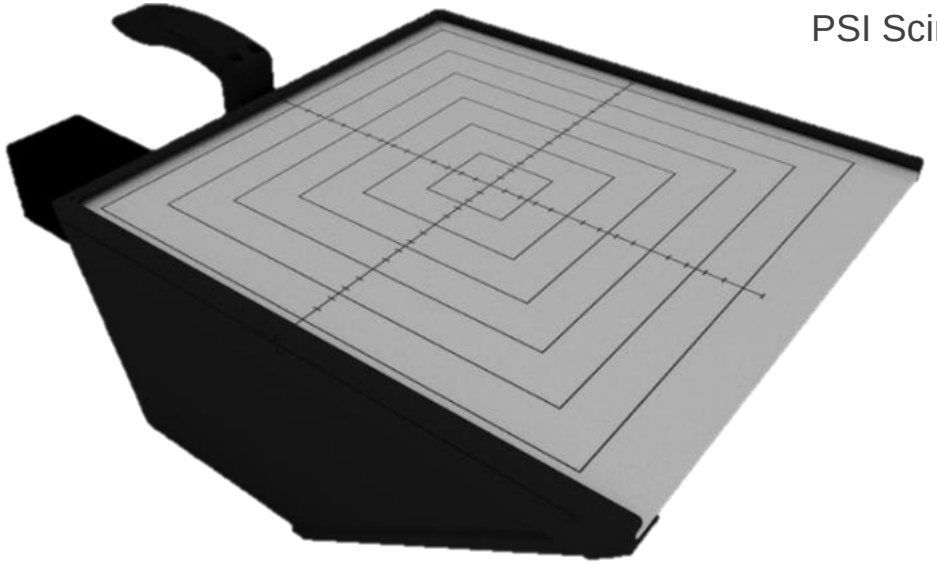
Measurement	Time
X	≃ 45 s
Y	≃ 45 s
Diagonal 1	≃ 45 s
Diagonal 2	≃ 45 s
Total per Spot	*≃ 3 min/spot*
Layer (100 spots)	≃ 300 min/layer
	≃ 5 h/layer
32 layers	≃ 160 h
	≃ 20 days

+ Multiple Gantry angles!

Alternatives

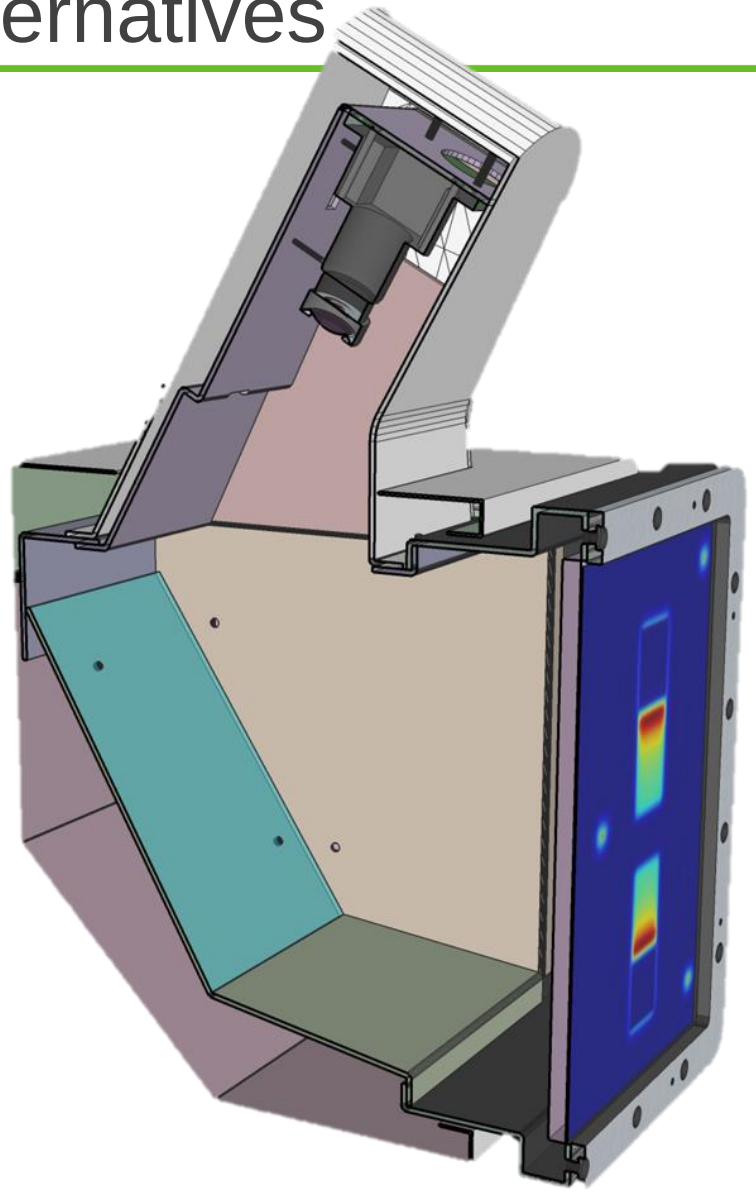
PSI Scintillator

IBA Dosimetry Lynx



Logos XRV-3000

Alternatives



Measure as fast as the beam is delivered

Typical delivery time for a 10x10 layer ≃ 1s

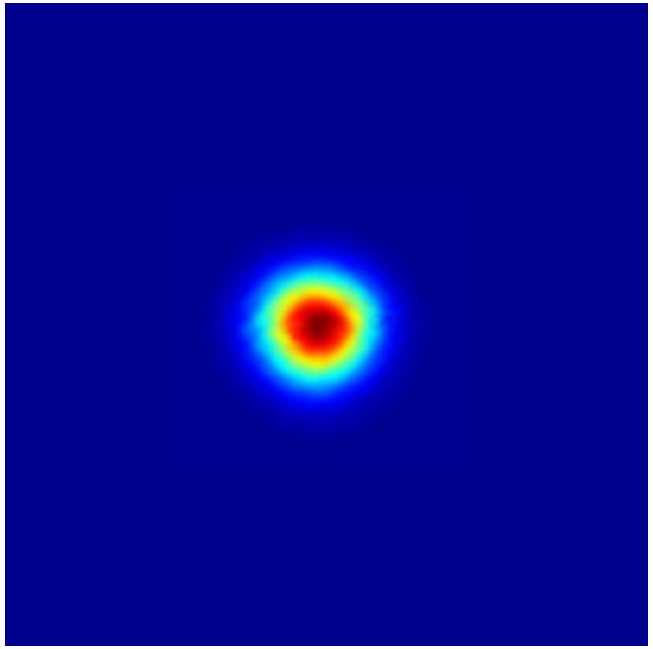
→ 32 layers ≃ 30 sec

(vs. 20 days)

/!\ geometric corrections

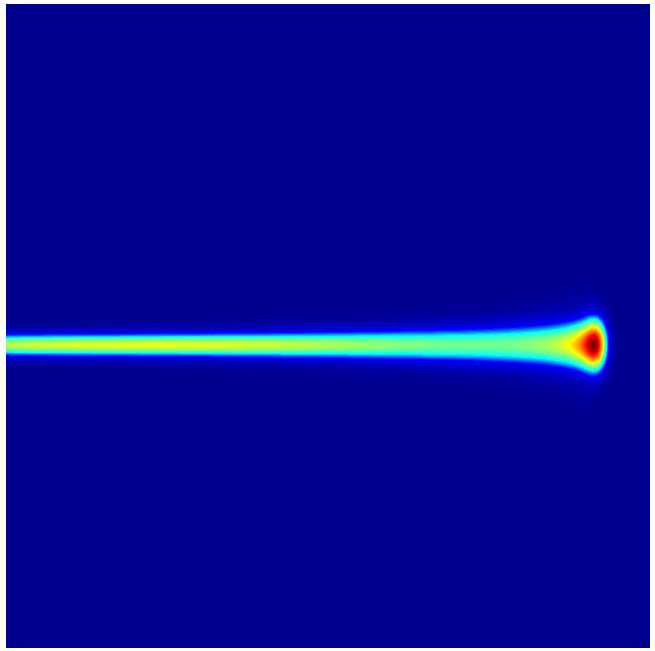
PBS is very simple

It is just a combination of:



Spots

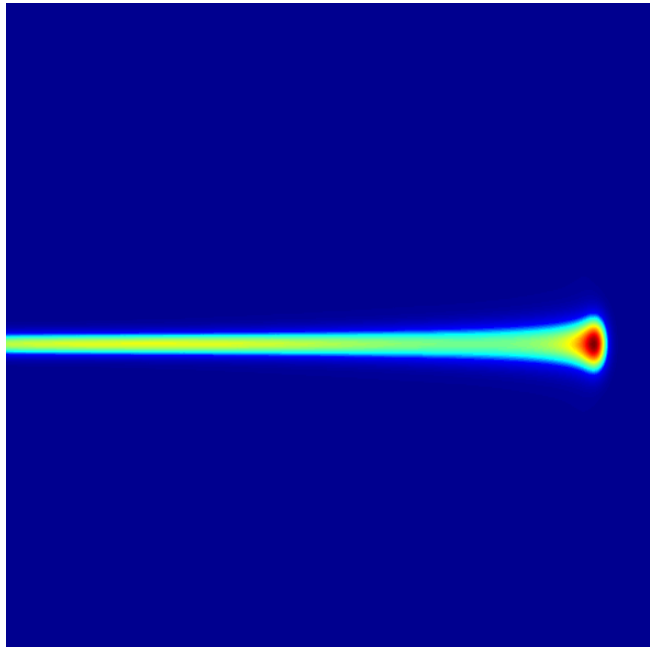
&



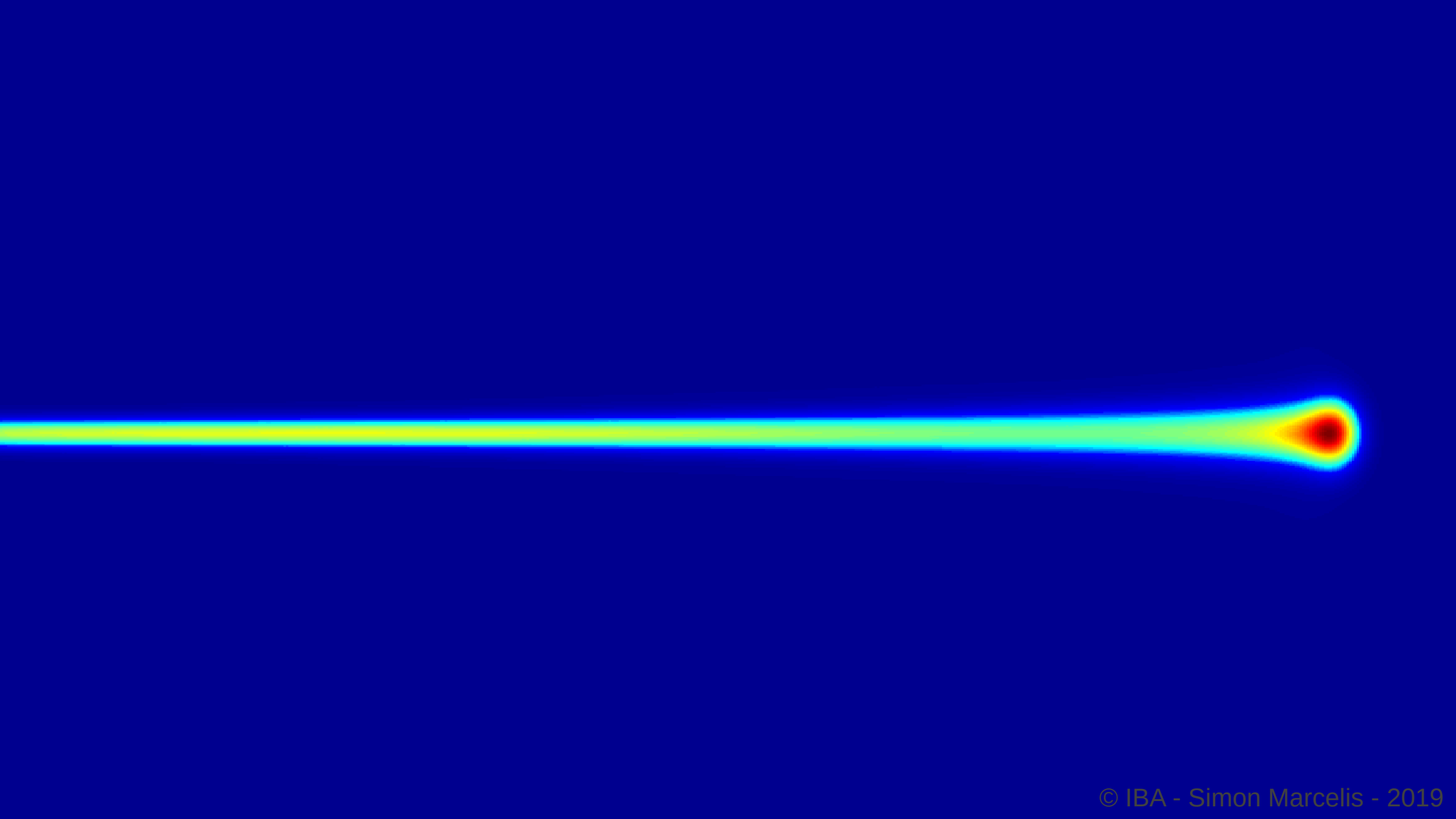
Bragg Peaks

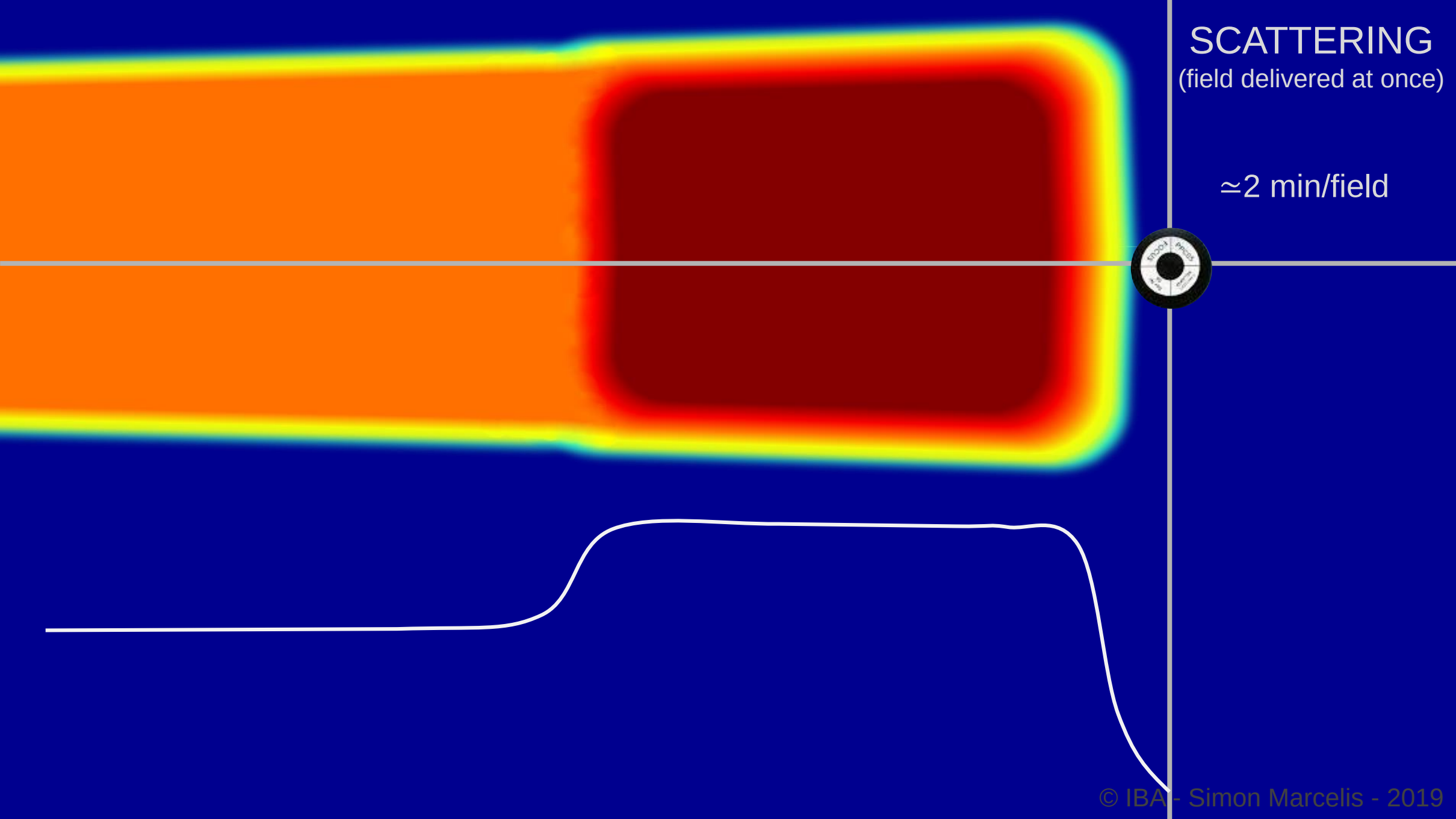
Both can easily be measured by a Water Phantom

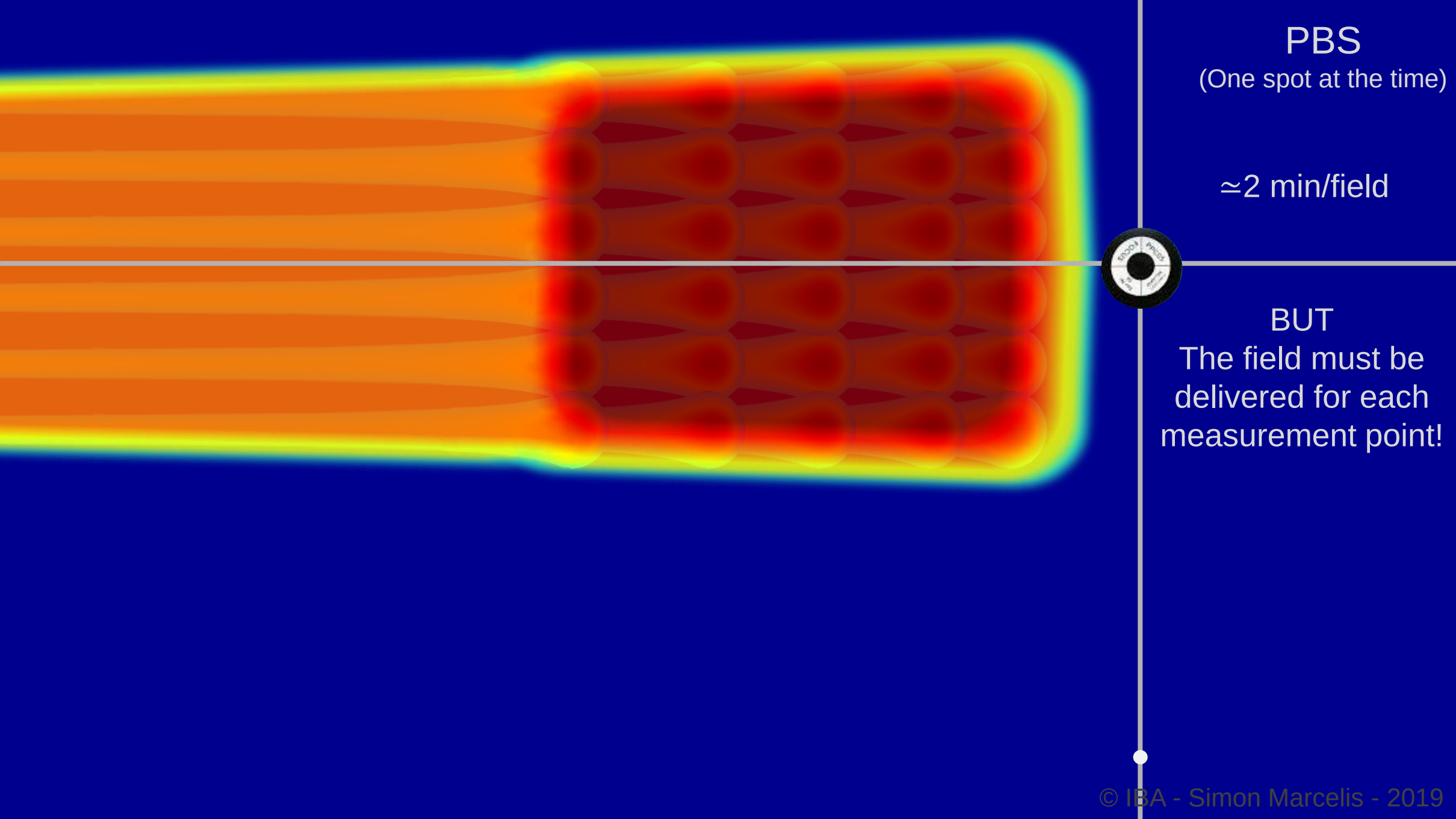
Bragg Peaks & SOBPs

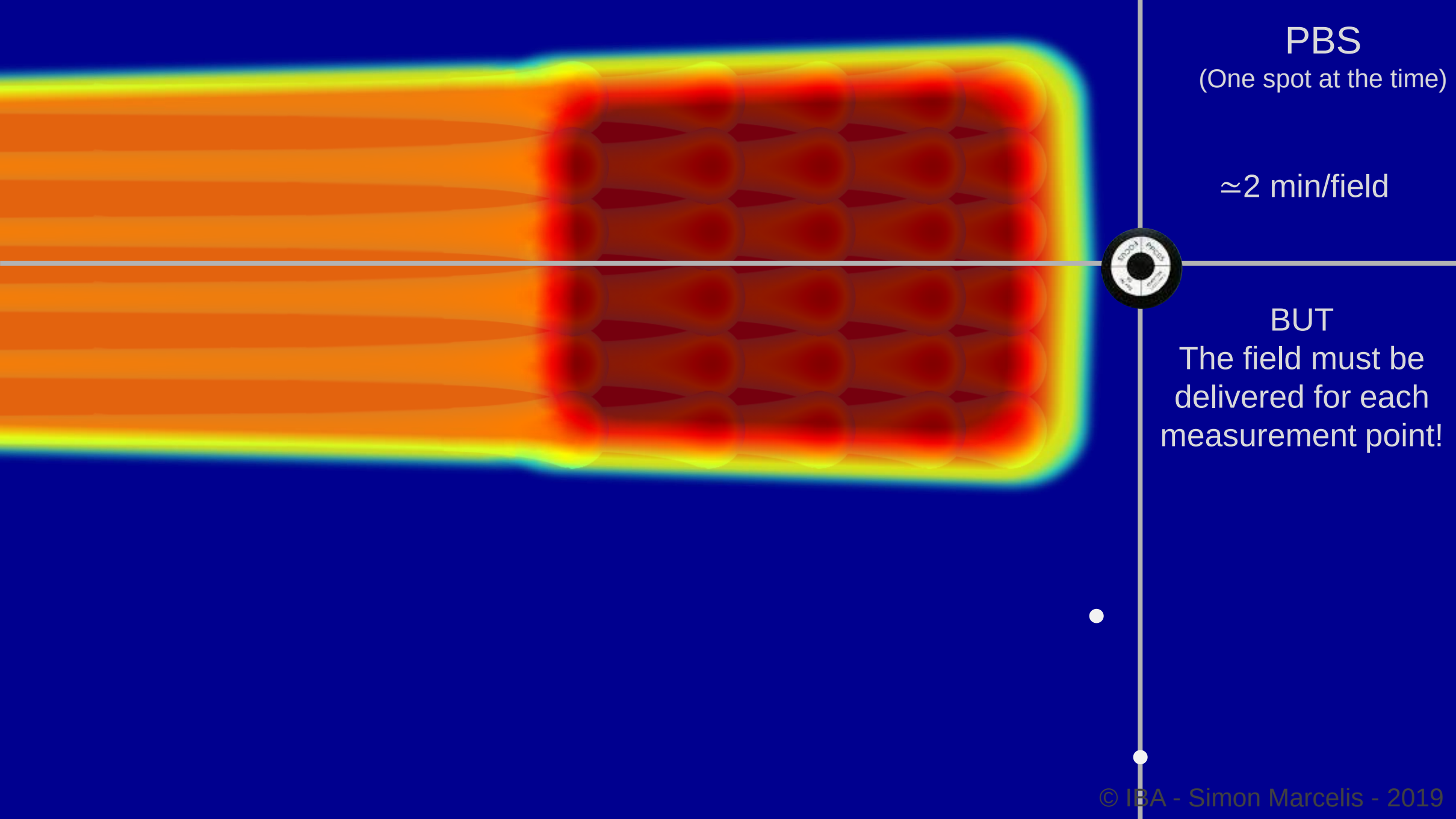


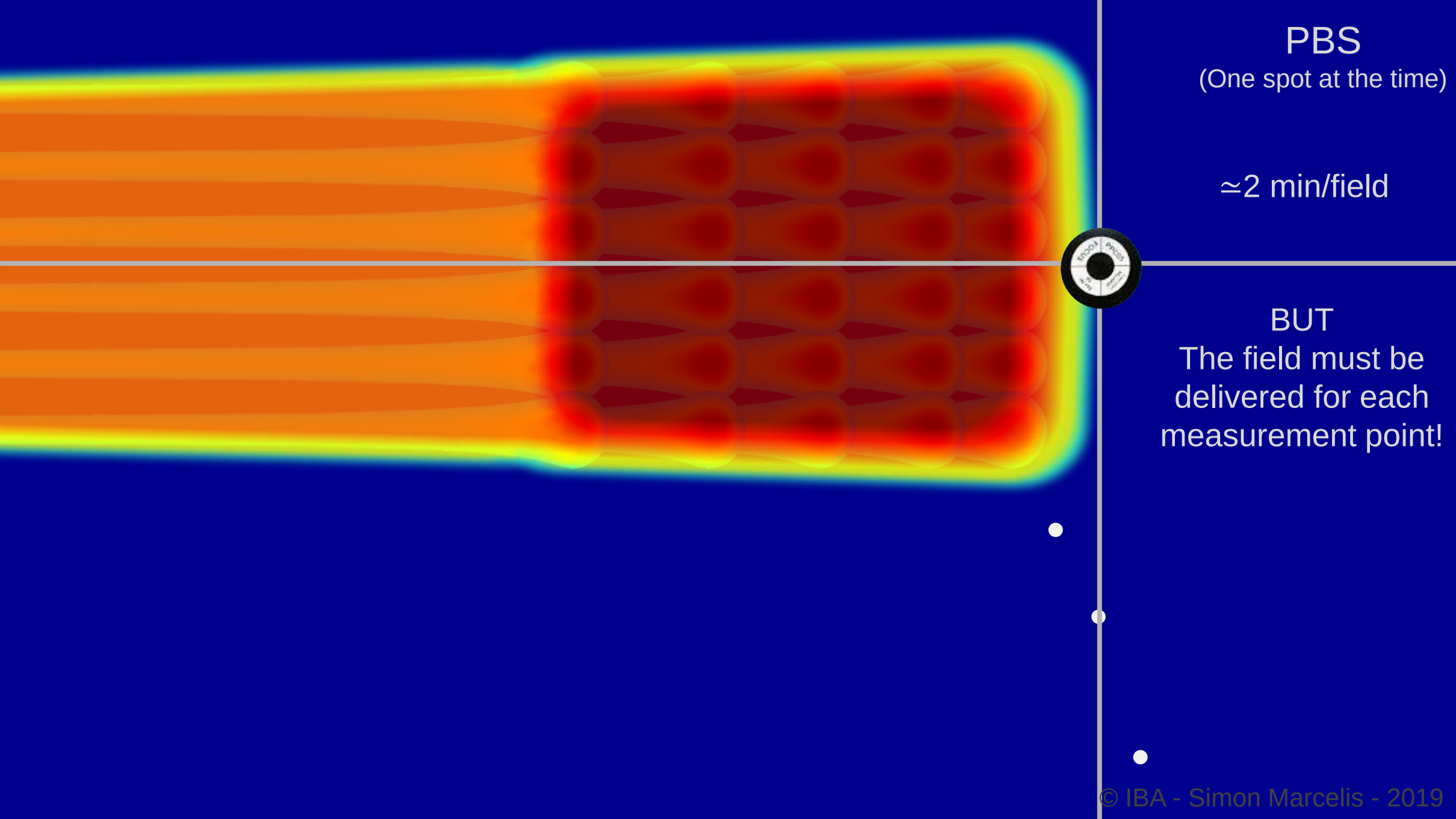
Bragg Peaks

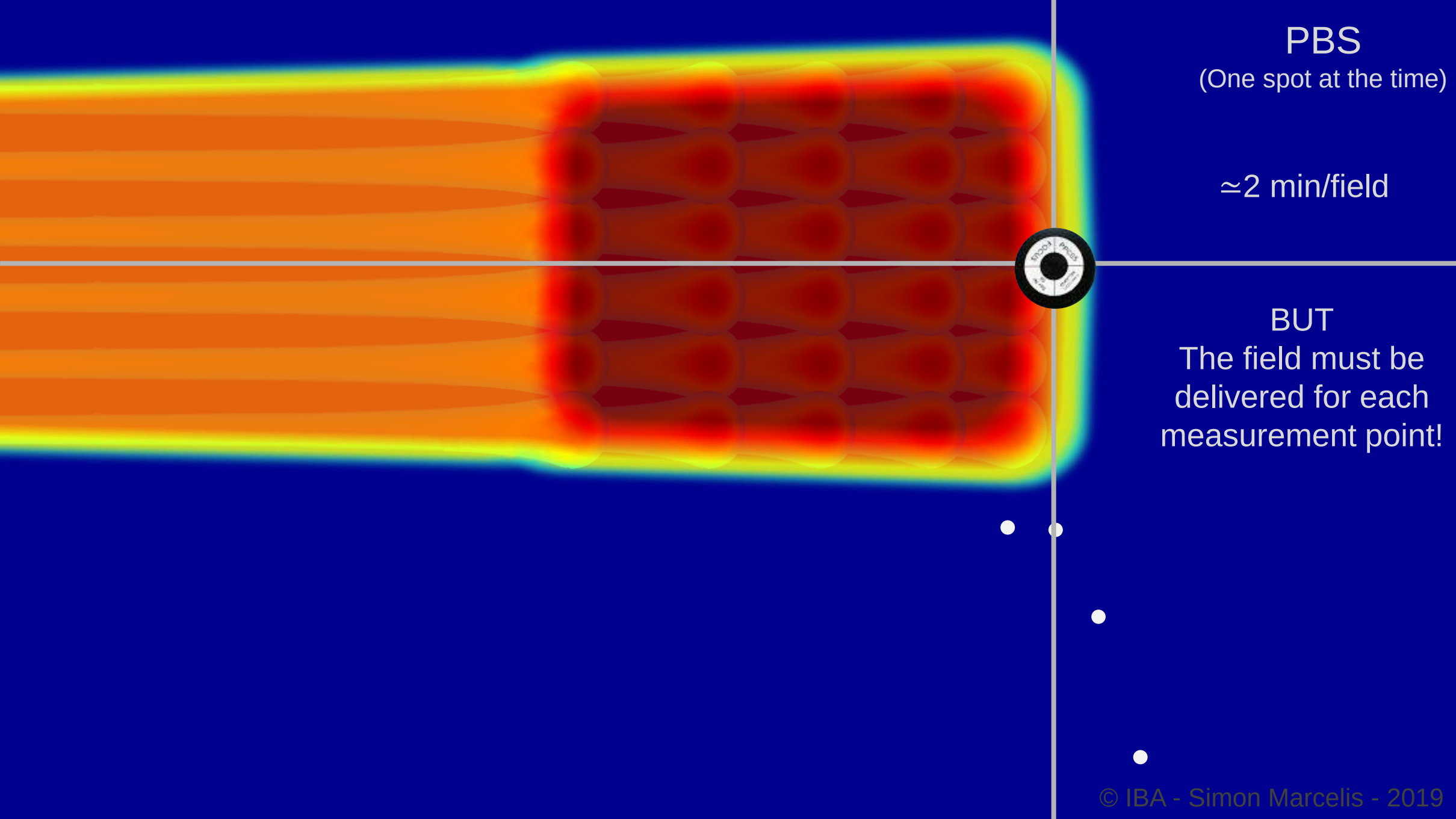


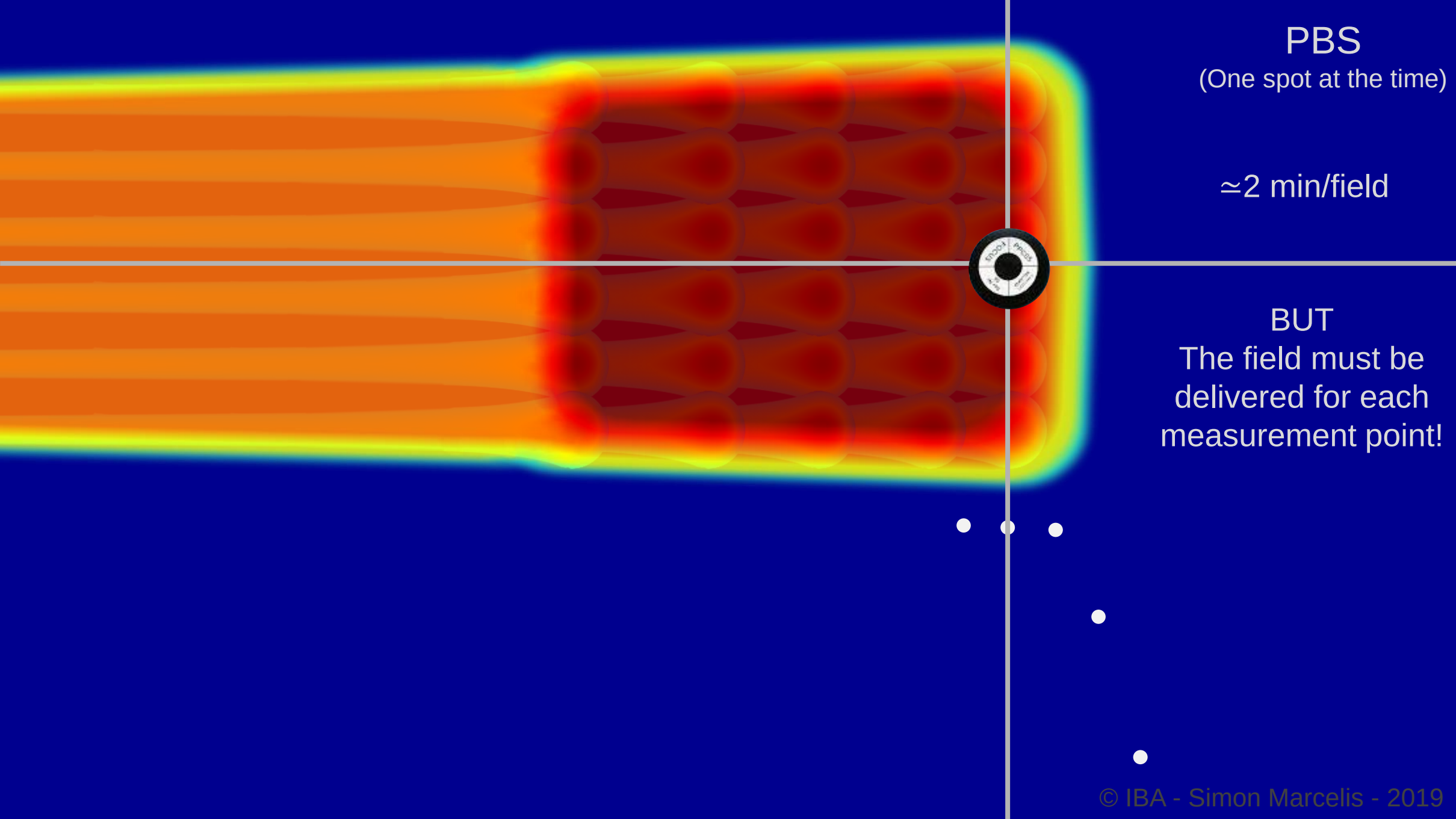


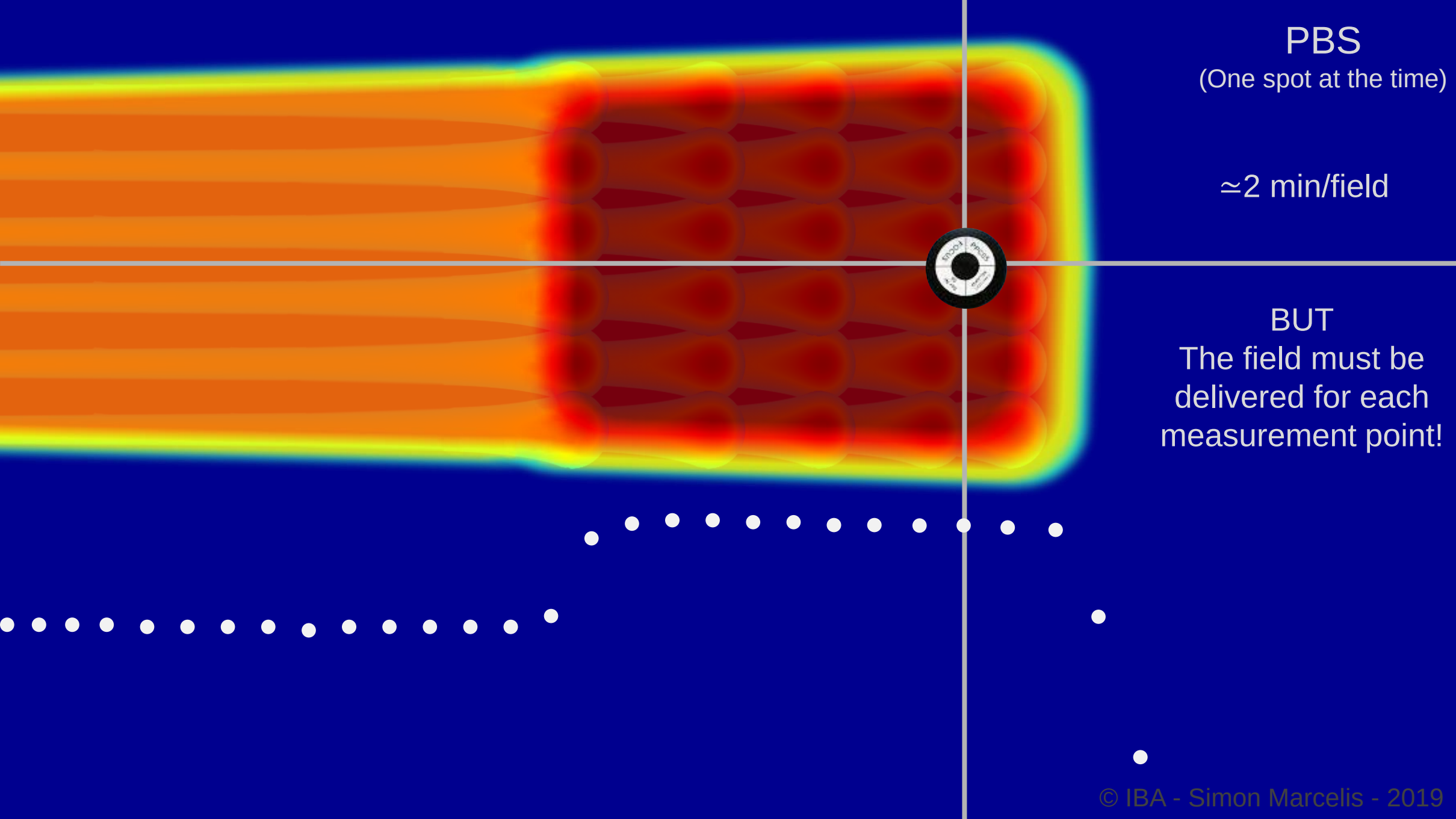


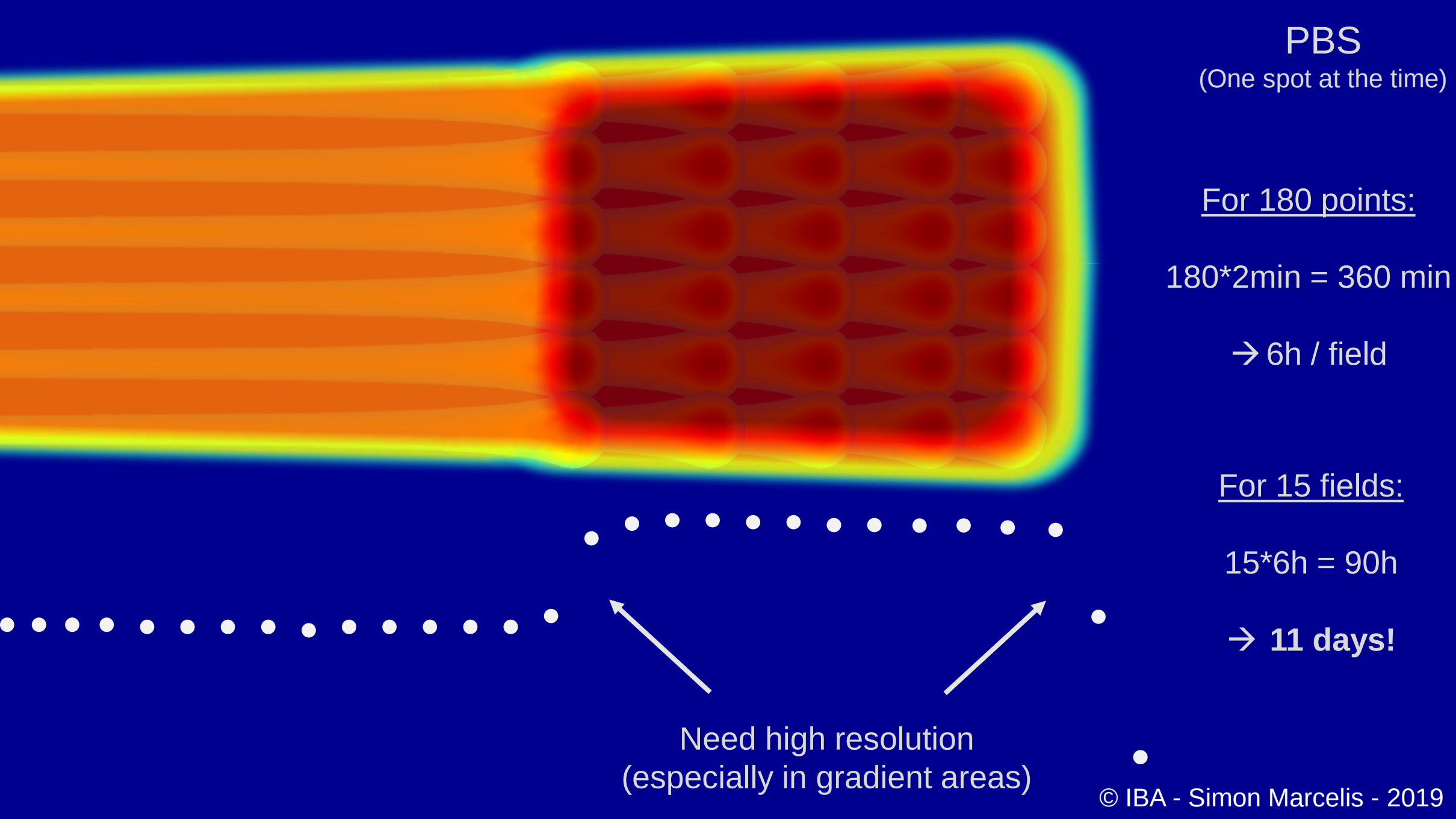










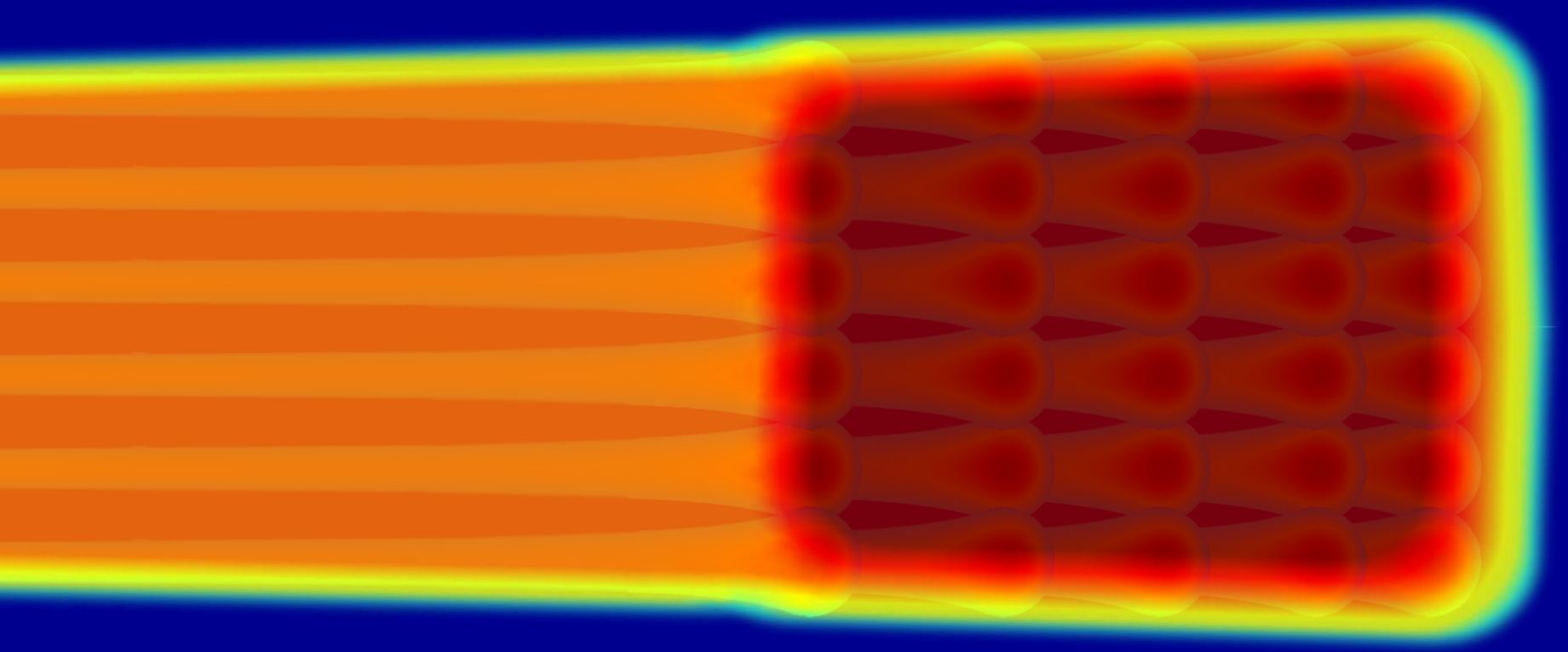


MLIC (Multi Layers Ionization Chambers)

DE.TEC.TOR QUBENEXT

IBA Dosimetry Zebra

Patent US8779375B2, Bruno Marchand and al. (2010)

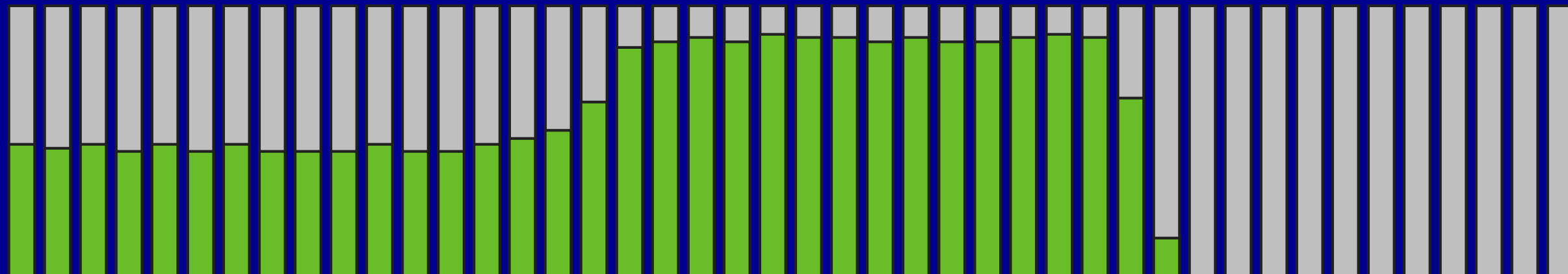


The MLIC will measure as fast as the system can deliver

Typical number of fields ≃ 15

→ 15*2 min/field = 30 min

(vs .11 days)



Dosimetry

Quality Assurance

Commissioning

Machine QA

Patient QA

Dosimetry

Quality Assurance

Commissioning

Machine QA

Patient QA

AAPM TG-224 Proton Machine QA

TABLE I. Daily QA procedures for proton therapy.

	DS/PS	US	PBS
Dosimetry			
Output constancy	±3%	±3%	±3%
Depth verification:			
Distal	±2 mm	±1 mm	±1 mm
Proximal	±2 mm	±2 mm	-
SOBP width	±2%/±2 mm	±2%/±2 mm	-
Spot position	-	-	±2/±1 mm
Imaging			
X-ray isocenter vs Laser isocenter		±2 mm	
X-ray and proton beam isocenter coincidence		±1 mm	

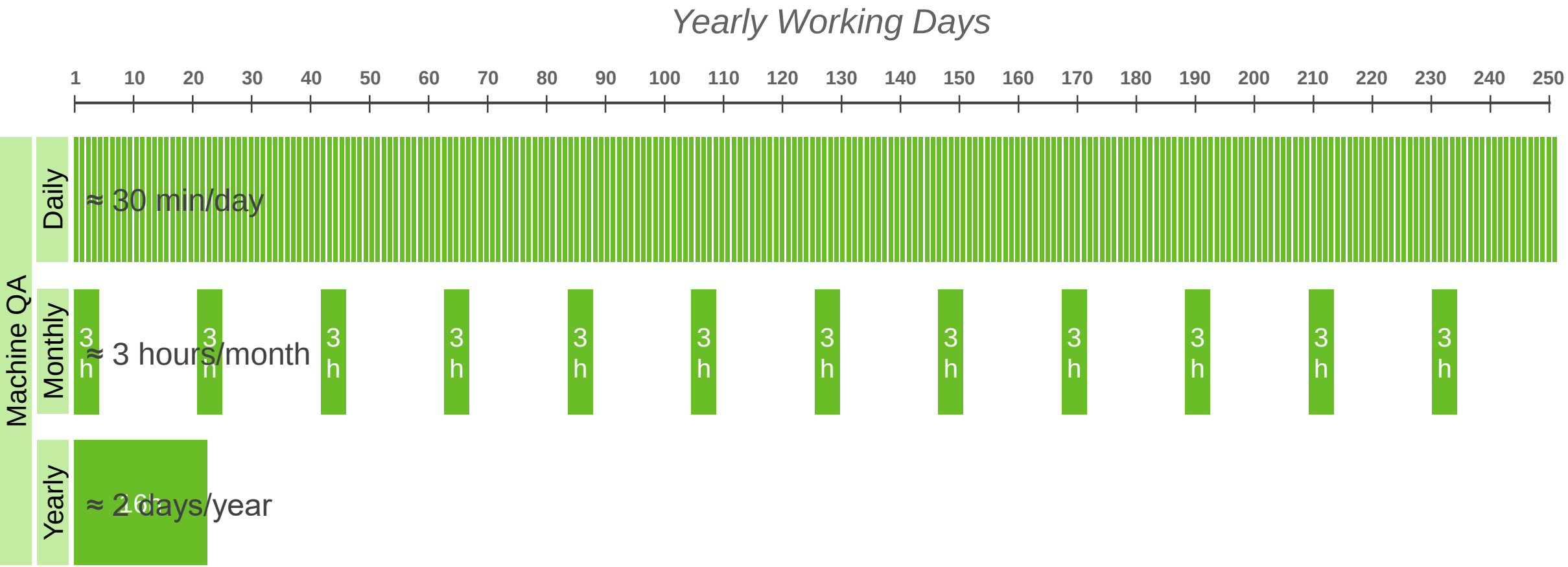
- Recently published (May 2019)
- B. Arjomandy, P. Taylor, C. Ainsley, S. Safai, N. Sahoo, M. Pankuch, J. Farr, SY. Park, E. Klein, J. Flanz

Current Practices

- Extensive analysis of QA common practices

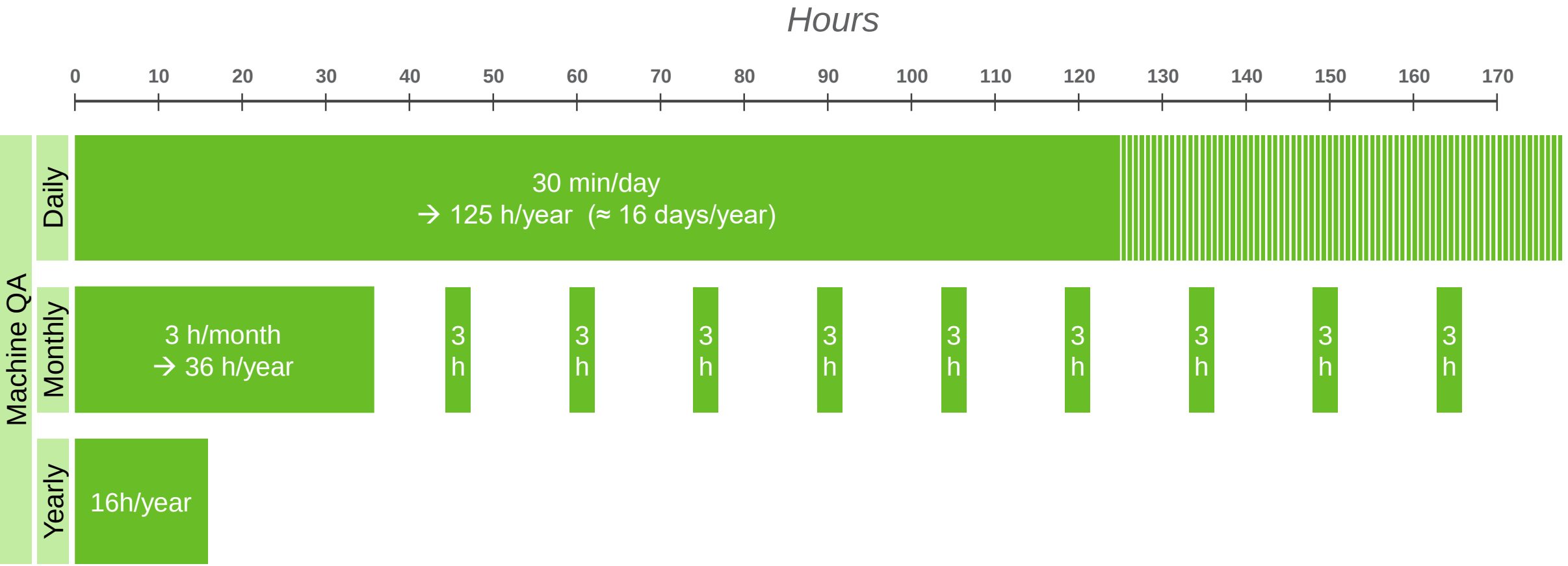
PT Site	DS	US	PBS	Frequence	Test	Tolerance	Device	Comment
Site C	✓	✓		Yearly	Dose Rate	± 30 %	PPC05 + WP	One field per option
Site A			✓	Yearly	Field Size	> 30×40	Film	Largest Field Size > 30×40
Site B			✓	Monthly	Test Pattern	γ 2%/2mm 98%	Lynx	160MeV 5cm solid water, 226.7MeV 5cm solid water
Site A			✓	Monthly	Spot Sigma	< 10% or 0.5 mm	Lynx	< 10% or 0.5 mm, whichever is smaller
Site C	✓	✓		Yearly	Modulation	± 3mm or ± 3%	PPC05 + WP	
Site A			✓	Daily	Spot Sigma	± 20%	I'mRT MatriXX + Buildup	CPASS ± 10 %
Site F			✓	Daily	Spot Sigma	± 10%	Daily QA 3	4 spots (220 MeV), Field size diodes
Site C	✓	✓		Yearly	Snout Motion	≤ 5 mm	Ruler	
Site C	✓	✓		Monthly	Modulation	± 3.0 mm or ± 3 %	PPC05 + WP	2 ref field + 1 other field (rotation)
Site C	✓	✓		Weekly	Modulation	± 3.0 mm or ± 3 %	Zebra	2 ref field + 1 other field (rotation)
Site A			✓	Daily	Modulation	± 3 mm	I'mRT MatriXX + Buildup	CPASS ± 2 mm
Site A			✓	Daily	Flatness	± 3 %	I'mRT MatriXX + Buildup	CPASS ± 2 %
Site A			✓	Daily	Symmetry	± 3 %	I'mRT MatriXX + Buildup	CPASS ± 2 %
Site D		✓		Daily	Symmertry	± 3 %	Daily QA 3	2 electron energy chambers @ mid-

Typical Machine QA times

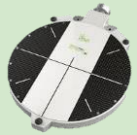


Source: 2015 survey, 14 answers

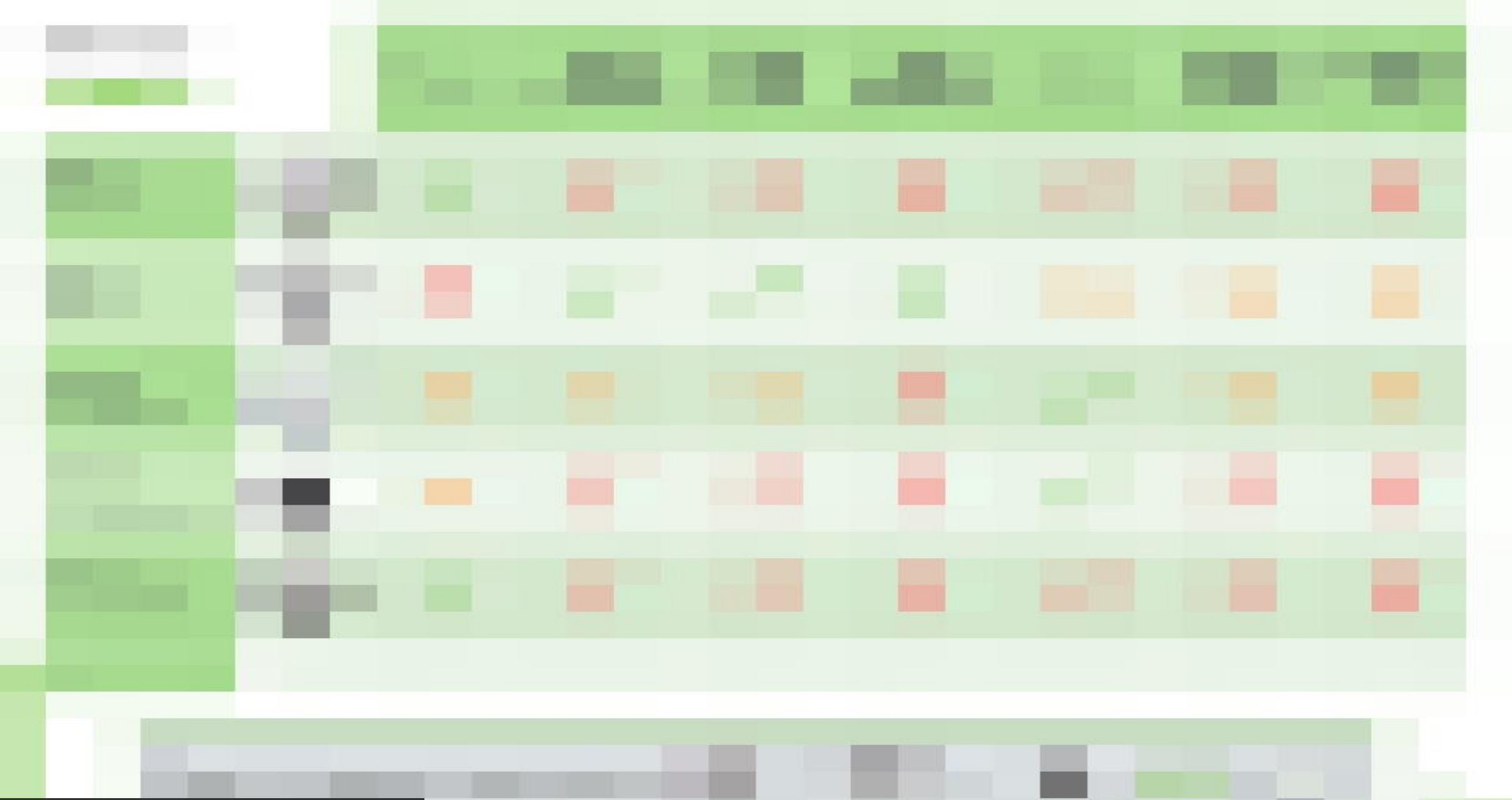
Typical Machine QA times



DEVICES SUMMARY

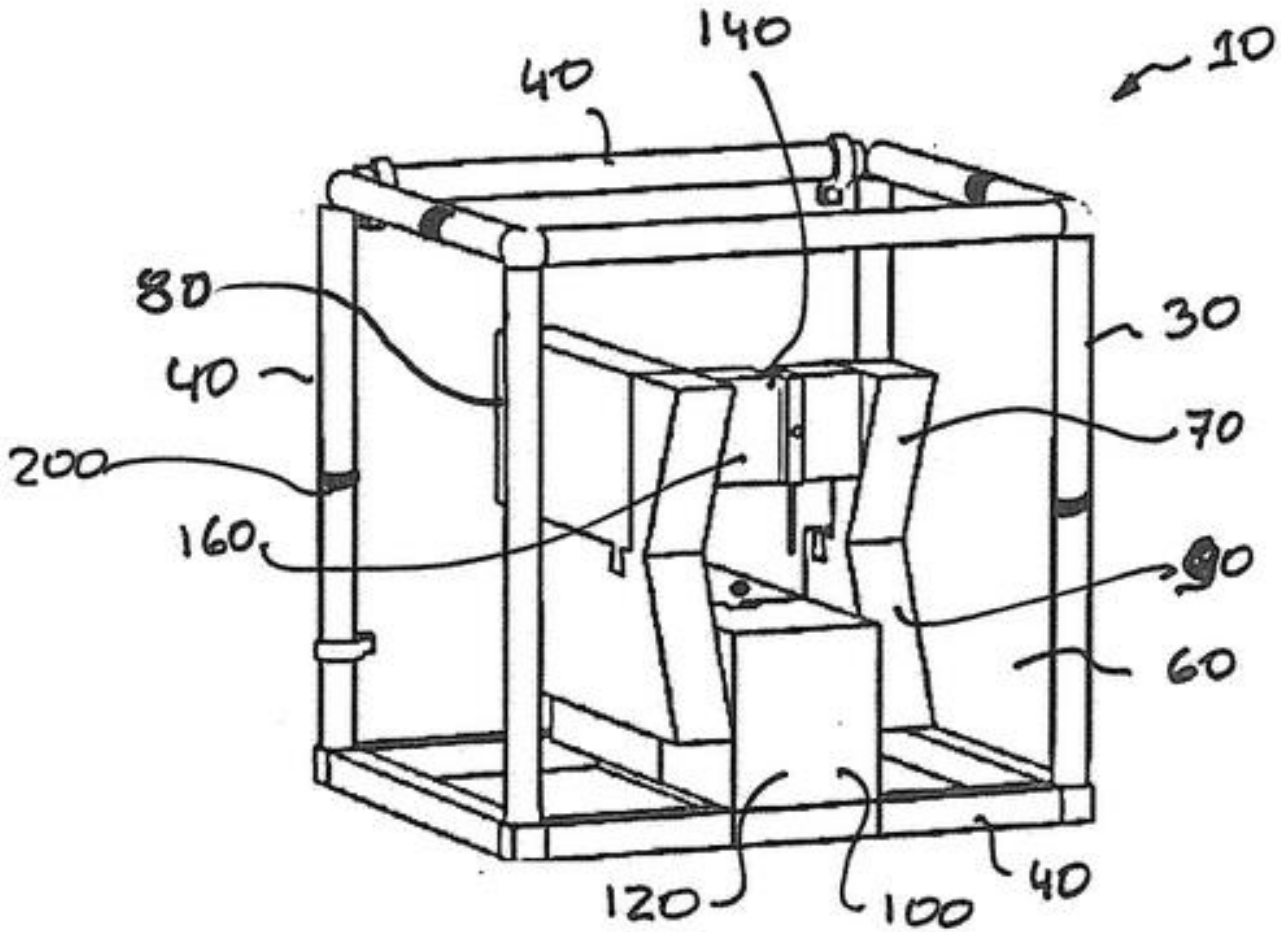
		Energy	Spots Positions	Spots Sizes	Spots Symmetry	Output	Imaging System	Beam vs X-ray
MLIC or equivalent		✓	✗	✗	✗	✗	✗	✗
Scintillator or films		✗	✓	✓	✓	≈	≈	≈
Array		≈	≈	≈	✗	✓	≈	≈
Parallel Chamber		≈	✗	✗	✗	✓	✗	✗
Large Chamber + water phantom		✓	✗	✗	✗	✗	✗	✗
…								

COMMON DAILY PRACTICES:  +  +  **OR** 



MatriXX: 32x32 (1 020) pixels

Daily QA Device



IN COLLABORATION WITH:

Northwestern Medicine Chicago Proton Center

PAUL SCHERRER INSTITUT PSI

WILLIS-KNIGHTON CANCER CENTER

Placidi et al, Z Med Phys., 28. 10.1016
Marcelis et al, EP3285869B1, Simon Marcelis et al.,

Daily QA Device

IN COLLABORATION WITH:

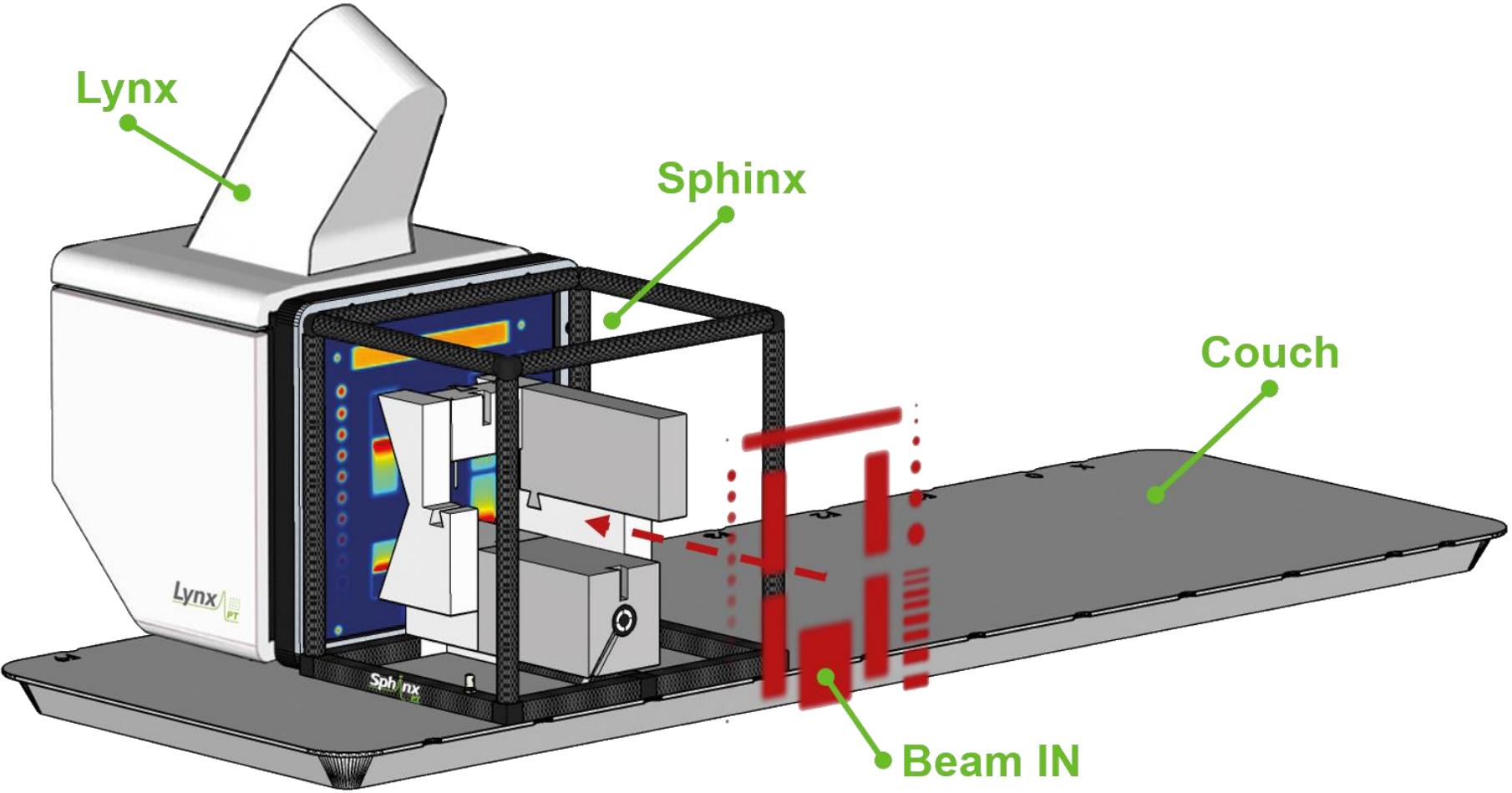
Northwestern Medicine Chicago Proton Center

PAUL SCHERRER INSTITUT PSI

WILLIS-KNIGHTON CANCER CENTER

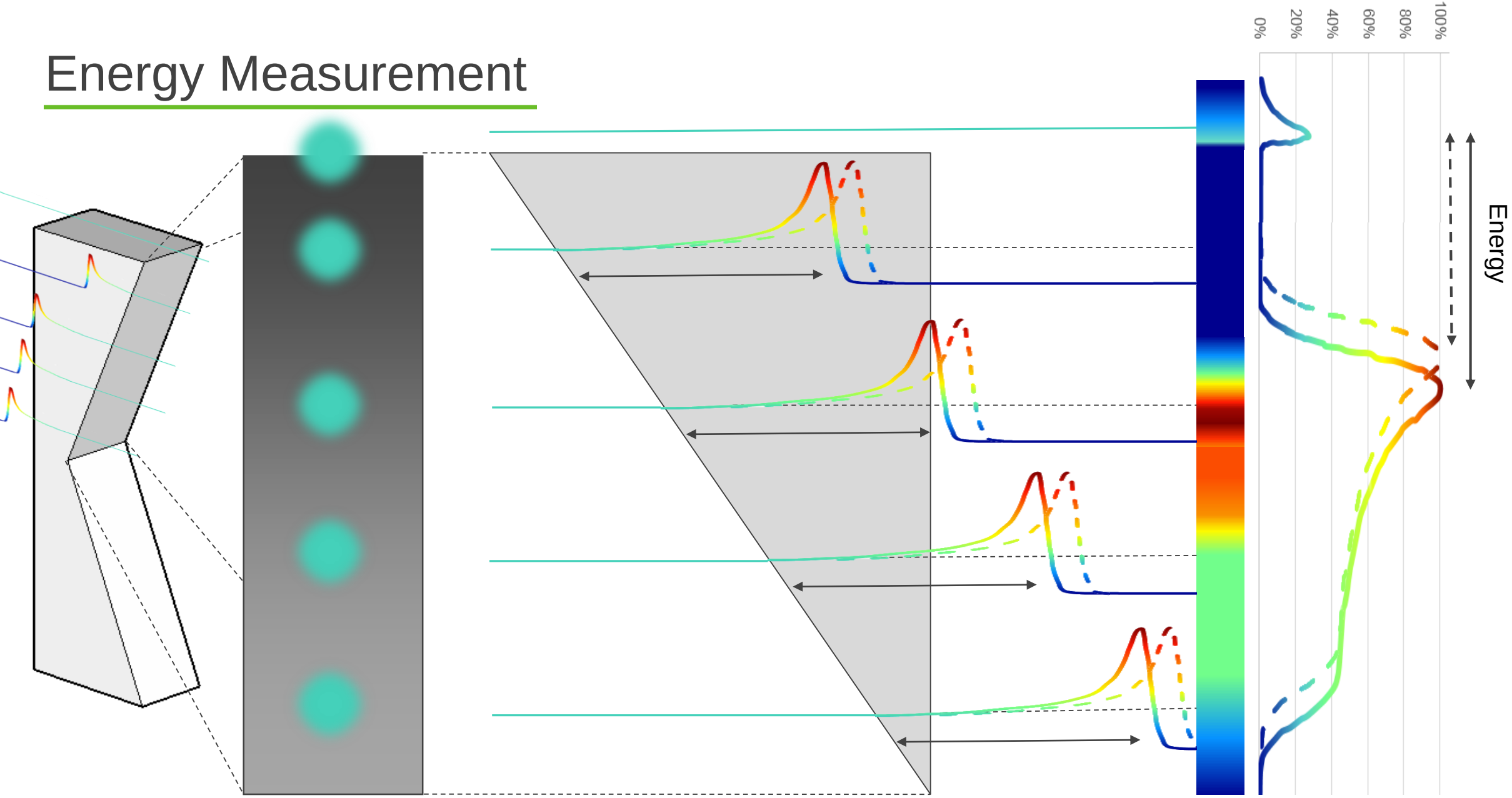
Placidi et al, Z Med Phys., 28. 10.1016
Marcelis et al, EP3285869B1, Simon Marcelis et al.,

Complete Daily QA in one shot



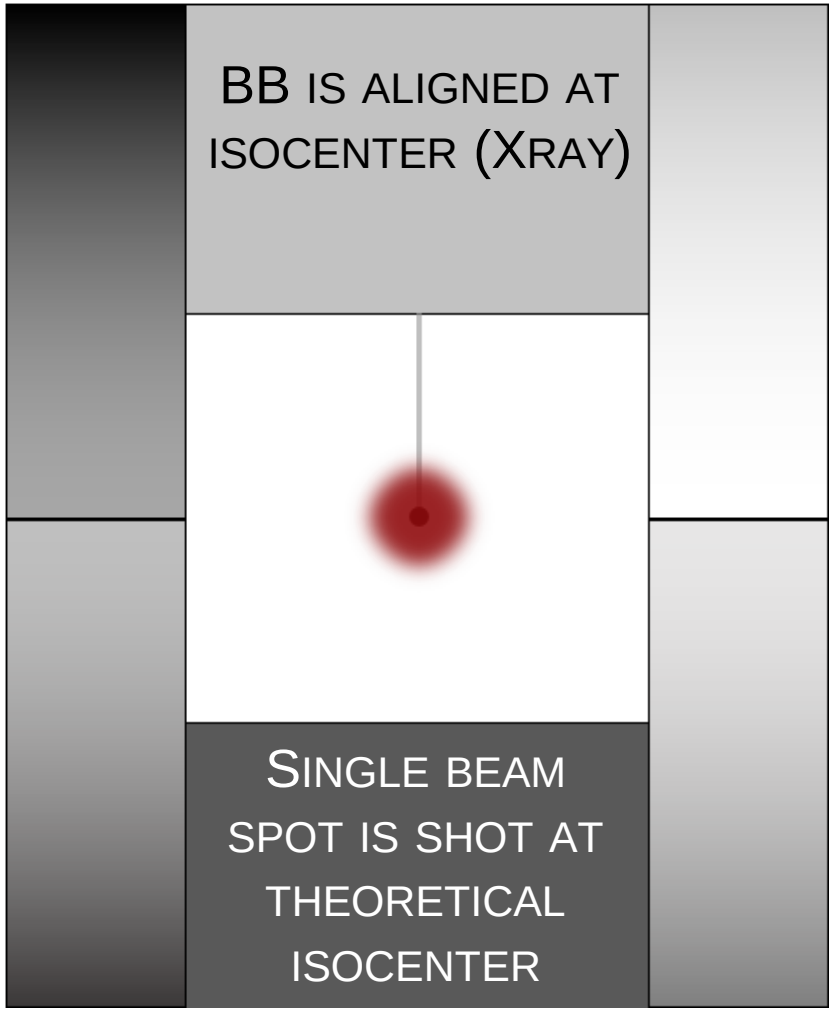
- ✓ Energy
- ✓ Spots Size
- ✓ Spots Position
- ✓ Spots Symmetry
- ✓ Absolute dose
- ✓ X-ray vs Proton
- ✓ Lasers
- ✓ Uniformity
- ✓ Imaging system
- ✓ Couch translation
- ✓ …

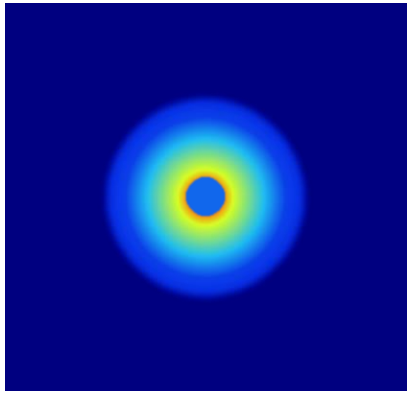
Energy Measurement



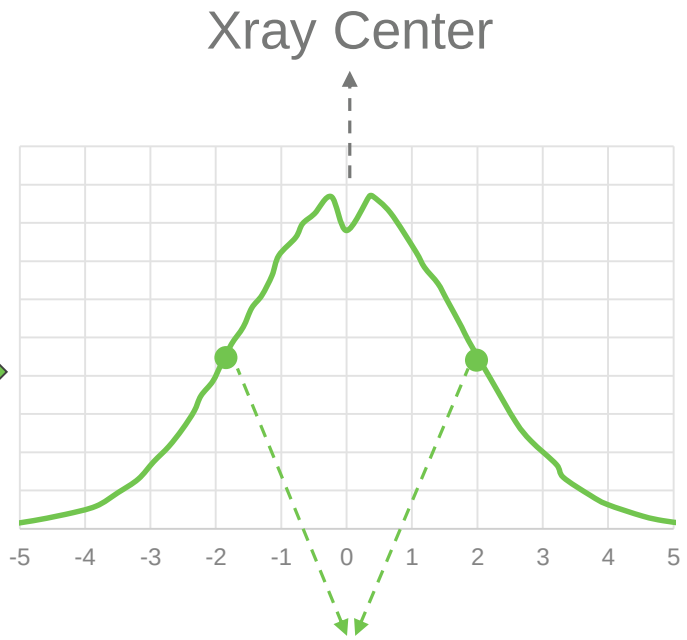
0% 100%

Beam vs. Xray





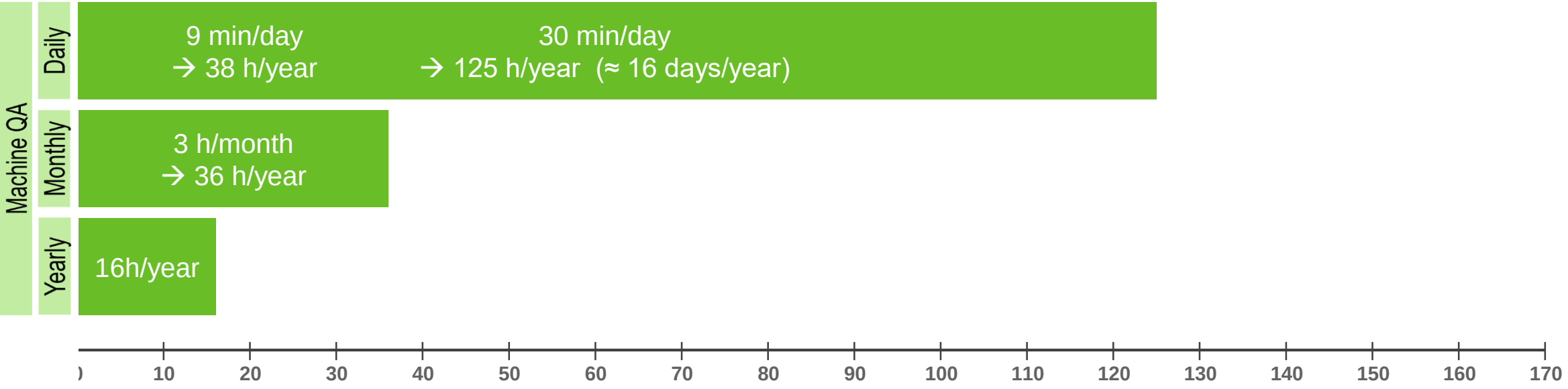
LYNX MEASUREMENT



Daily QA Device (Sphinx)

Daily QA in < 10 min

= 1 more patient/day



Dosimetry

Quality Assurance

Commissioning

Machine QA

Patient QA

Dosimetry

Quality Assurance

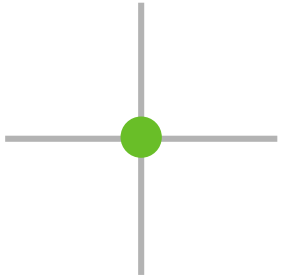
Commissioning

Machine QA

Patient QA

Evolution of Patient QA[1]

1973 → 2004



1D

Water Phantom

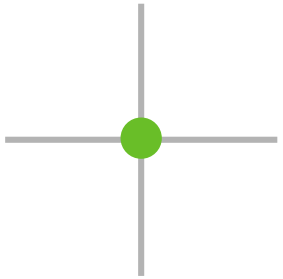
2D

Array

[1] Dates reflects the 1st available commercial solution

Evolution of Patient QA[1]

1973 → 2004 → 2012



1D

Water Phantom

2D

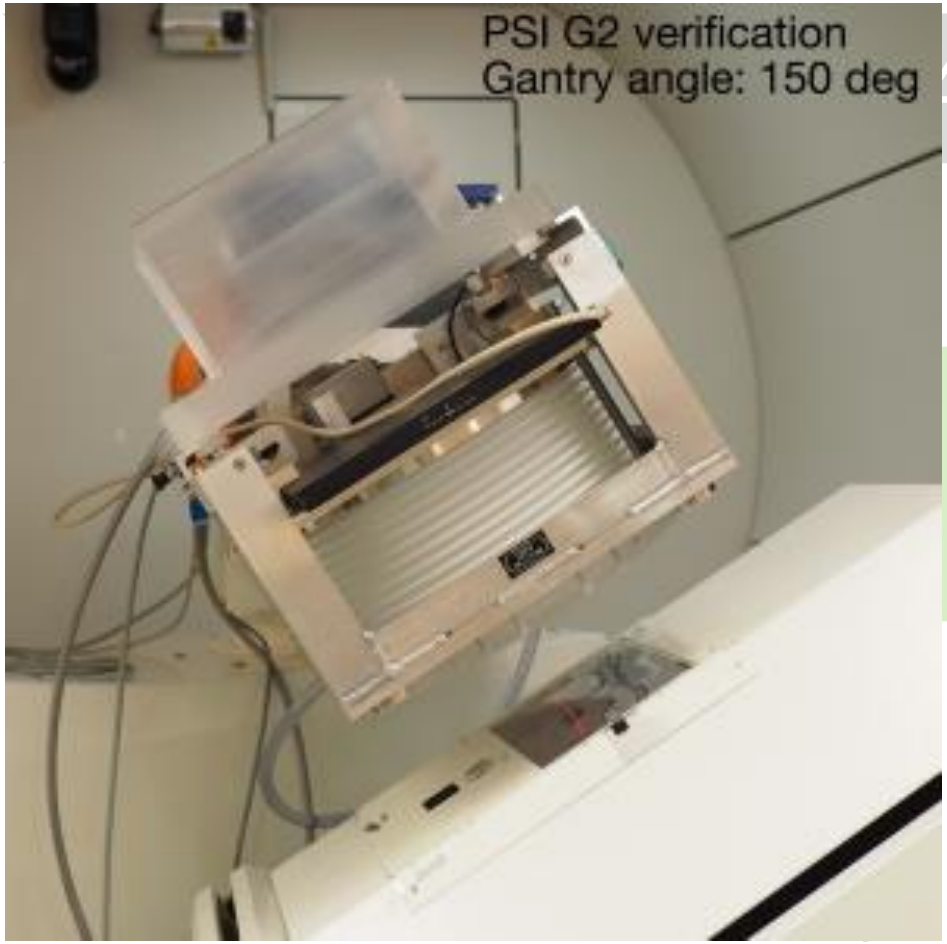
Array

2.5D

Arrays in Water

[1] Dates reflects the 1st available commercial solution

Evolution of Patient QA[1]

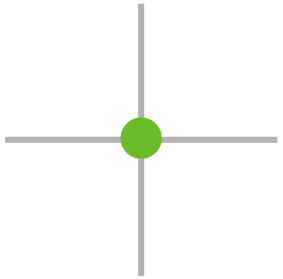


PSI Water Column Phantom

IBA DigiPhant

[1] Dates reflects the 1st available commercial solution

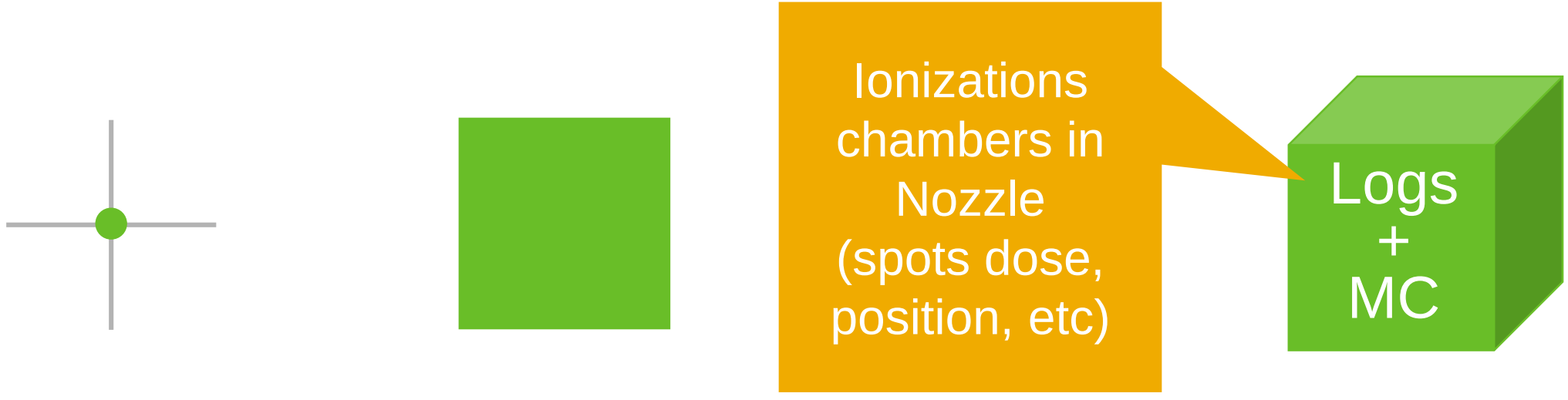
Evolution of Patient QA

1973	2004	2012	2019
			
1D	2D	2.5D	3D
Water Phantom	MatriXX	DigiPhant	3D Hardware ?

[1] Dates reflects the 1st available commercial solution

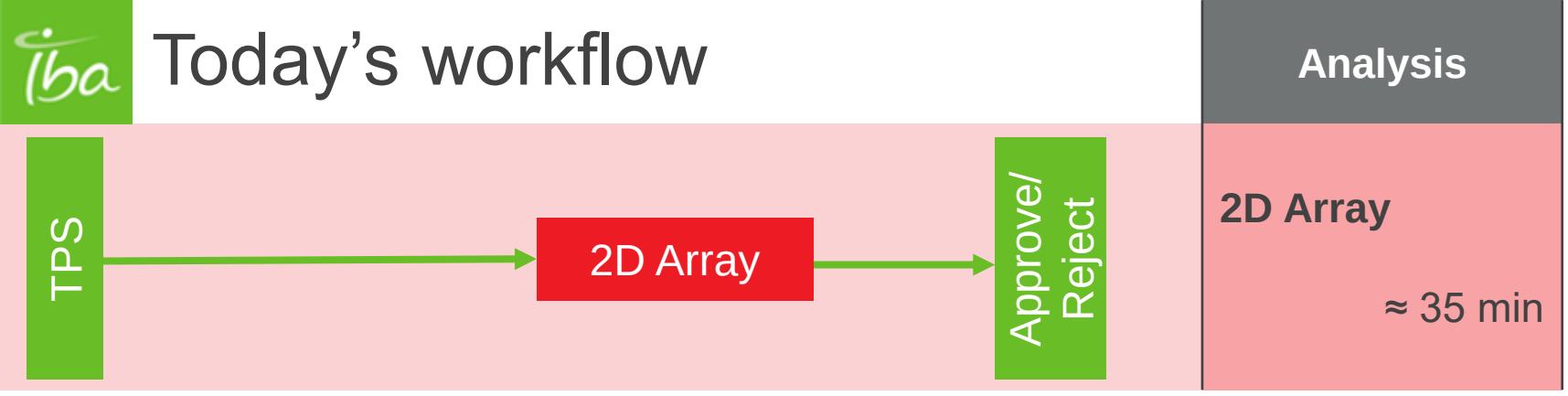
Evolution of Patient QA

1973	2004	2012	2019
1D	2D	2.5D	3D
Water Phantom	MatriXX	DigiPhant	3D ~~Hardware~~

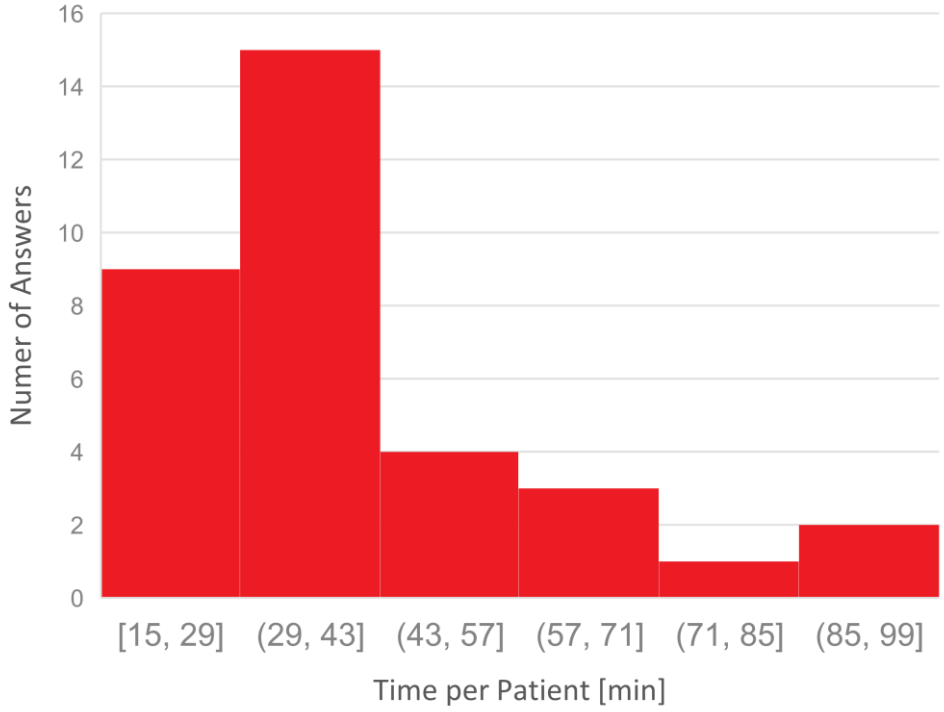


Machine Logs
+ Monte Carlo Indpt Dose

Today's workflow



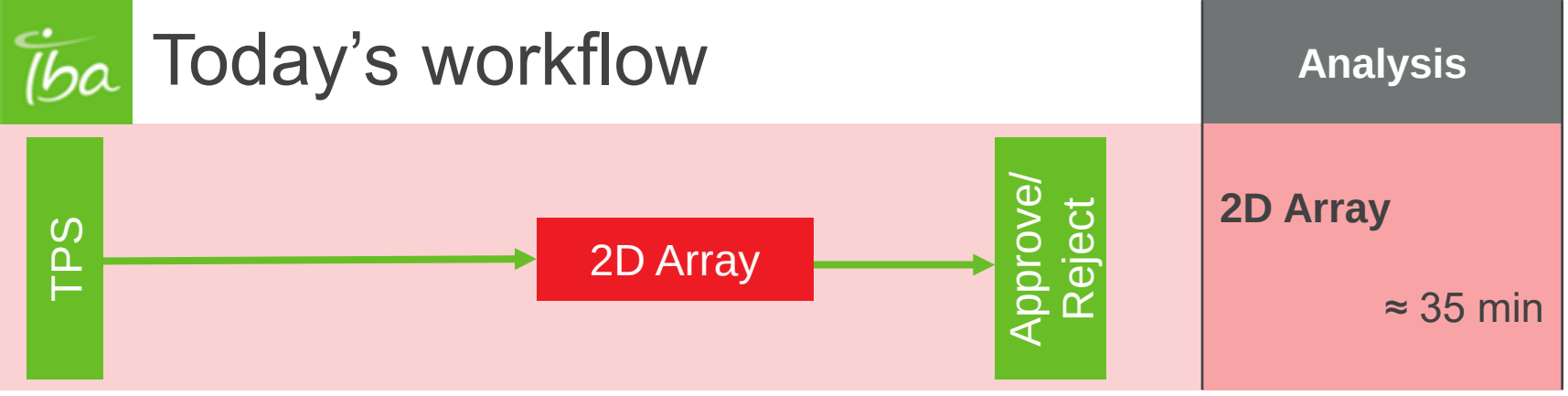
How much time do you spend on Patient QA per patient?



→ Average ≈ 35 min/patient

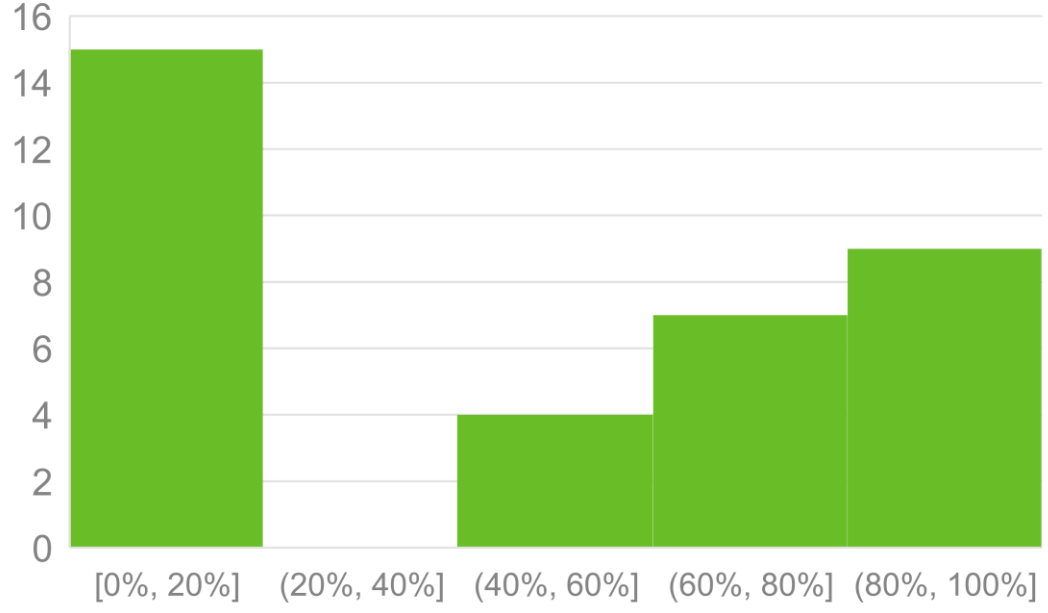
Source: Simon Marcelis, PT Facilities survey, Dec 2018, 37 participants

Today's workflow

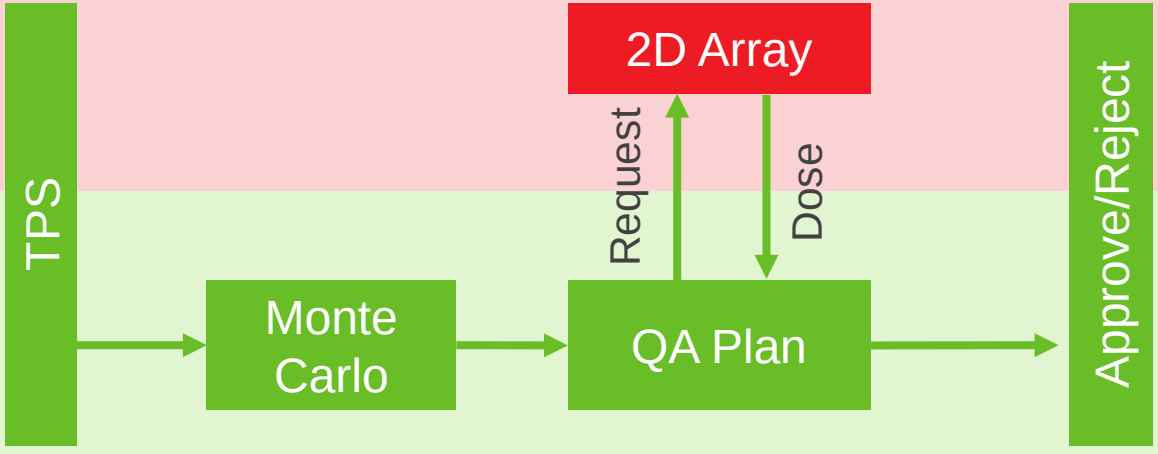


What percentage of patients would you QA using independent dose recalculation (Monte Carlo) only?

→ Average ≈ 50%



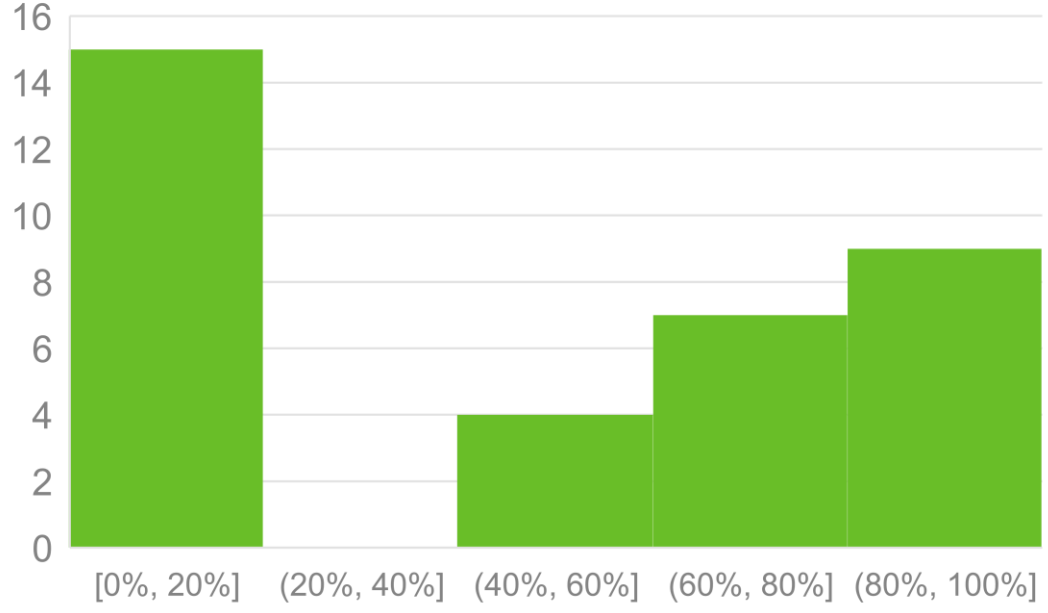
Tomorrow's Workflow



Analysis	Today	Tomorrow
2D Array ≈ 35 min	**100%** (35 min)	**50%** (18 min)
Monte Carlo = 0 min	0 % (0 min)	**50%** (0 min)

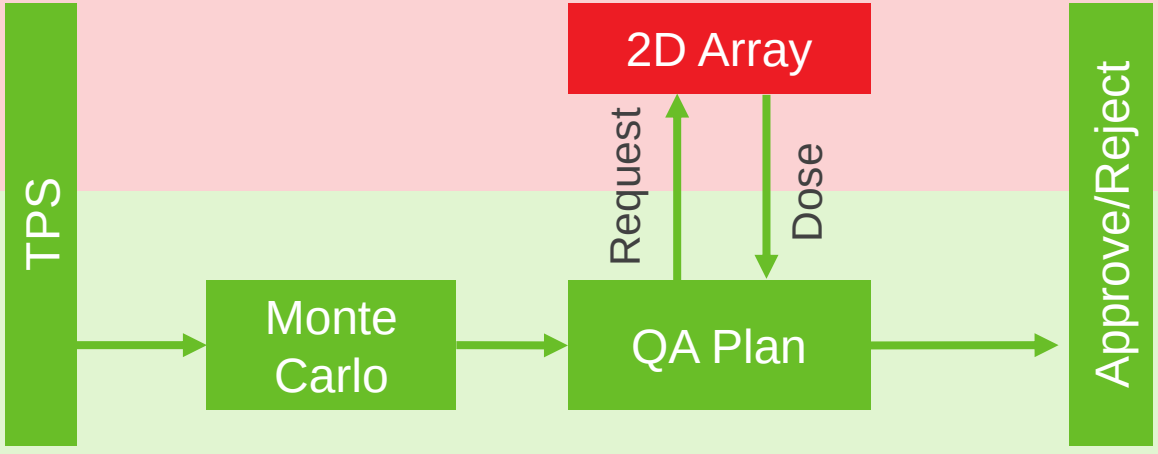
What percentage of patients would you QA using independent dose recalculation (Monte Carlo) only?

→ Average ≈ 50%

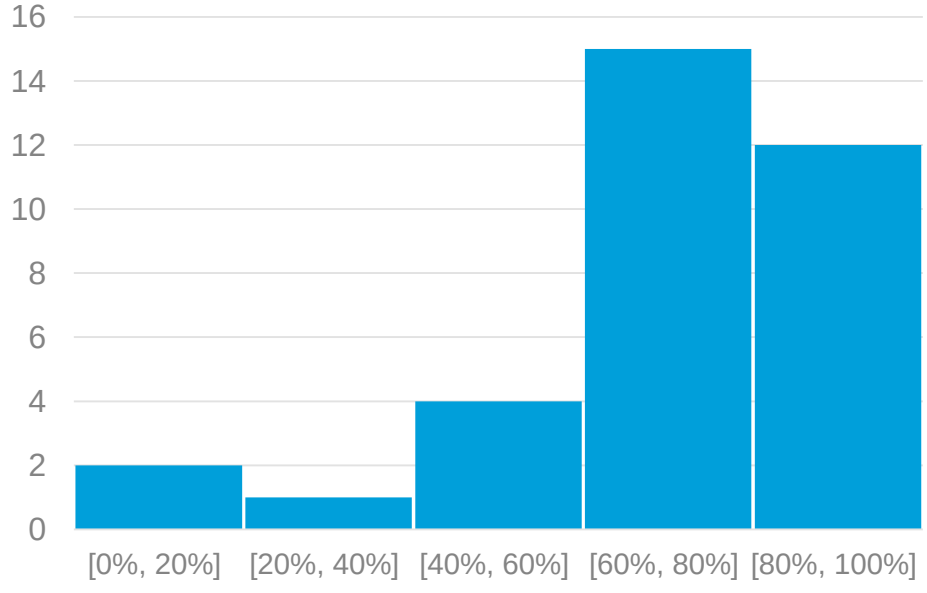


Source: Online survey, Dec 2018, 37 participants

Patient QA Workflows



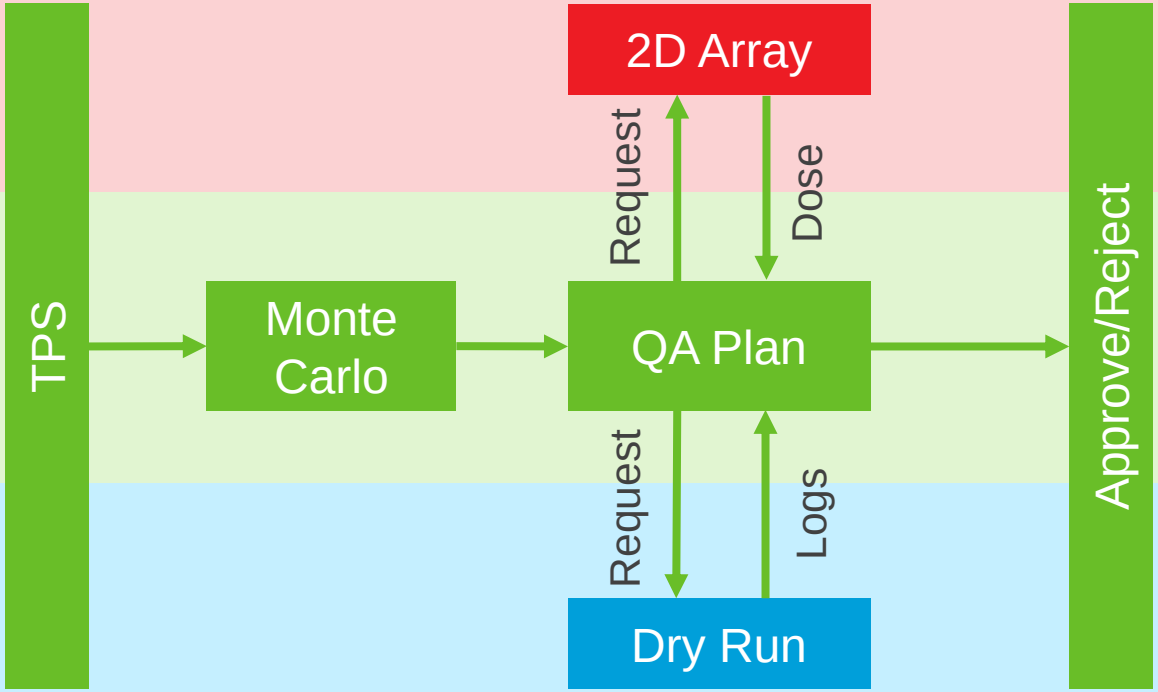
Analysis	Today	Tomorrow
2D Array ≈ 35 min	**100%** (35 min)	**20%** (7 min)
Monte Carlo = 0 min	0 % (0 min)	**50%** (0 min)



What percentage of patients would you QA using independent dose recalculation AND log based QA?

→ Average ≈ 80%

Patient QA Workflows



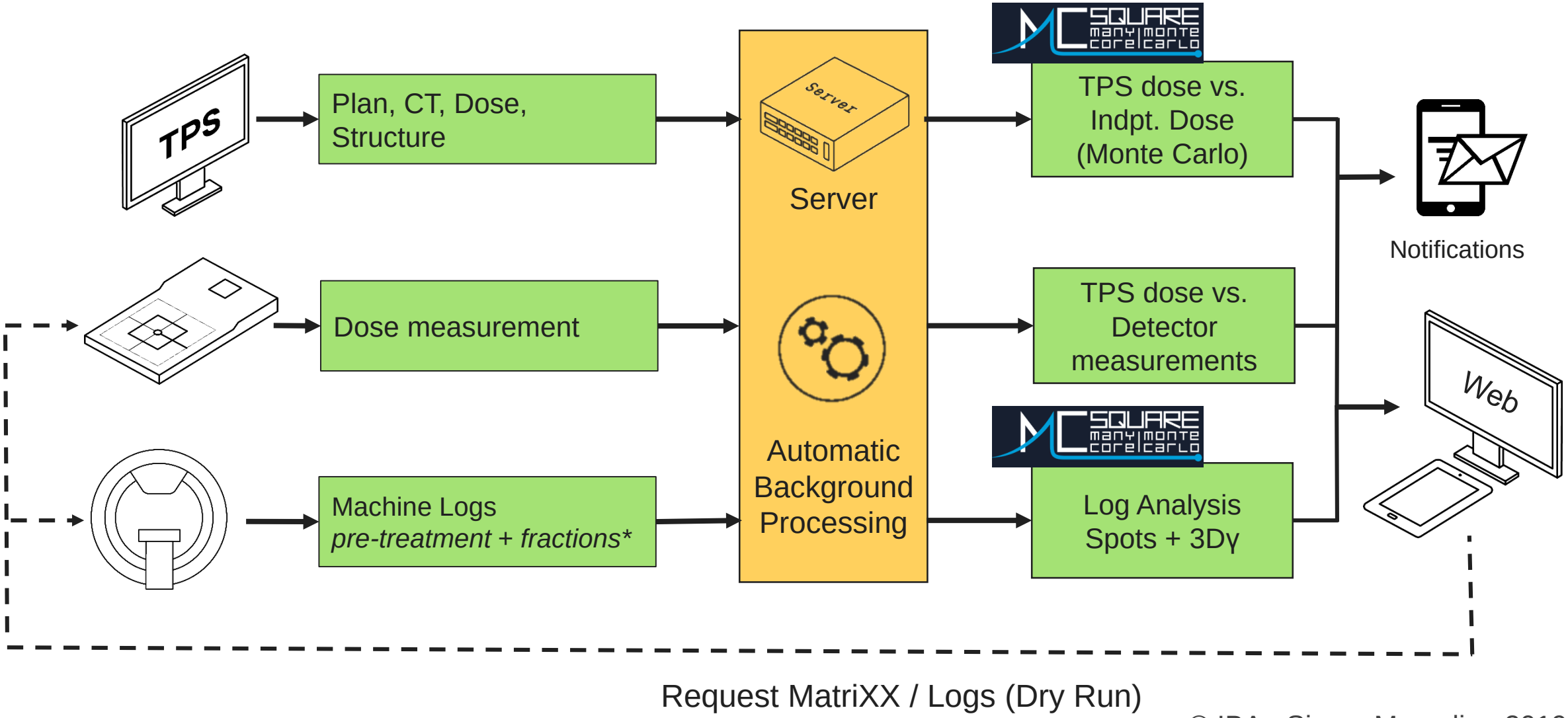
Analysis	Today	Tomorrow
2D Array (+MC) ≈ 35 min	**100%** (35 min)	**20%** (7 min)
Monte Carlo = 0 min	0 % (0 min)	**50%** (0 min)
Log (Dry Run) (+ MC) ≈ 10 min	0 % (0 min)	**30%** (3 min)
Avg. per patient	35 min	10 min
∑ per week (250pat./year)	175 min (≈3h)	50 min

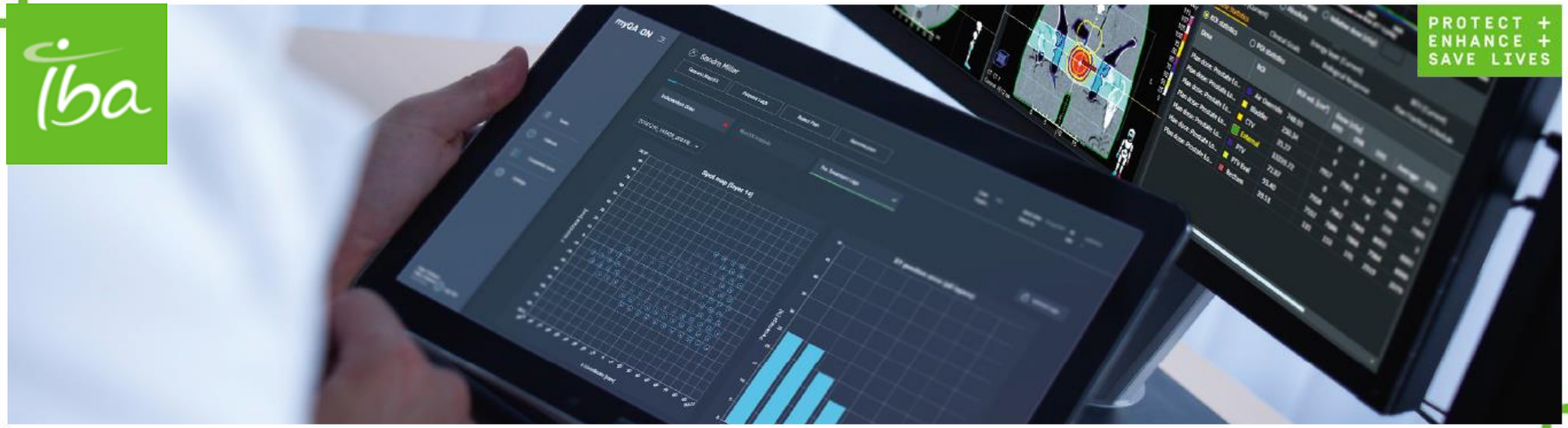
> 3x faster

Save up to 14 shifts (8 hours) per year (>2h/week)

+ Increase the quality of your Patient QA
+ Verify each fraction (log)

Patient QA Workflow





Thank you!