USE OF MULTIPLE BUNCHES TO ACHIEVE DOSE PEAK AT WATER DEPTH APPLYING A KICKER AND SOLENOID MAGNETS

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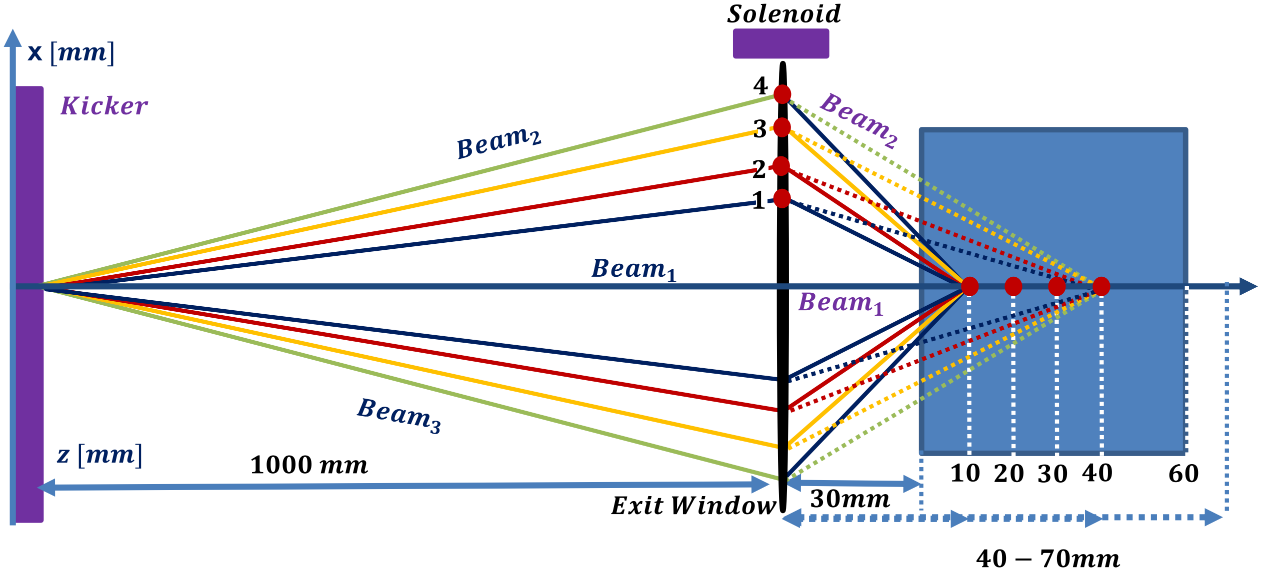
GOAL OF THE STUDY

The main goal of this study was to evaluate the energy deposition peak and the position in the water when more than one bunch enters the water.
To implement the intersection of several bunches at one point a depth of water, a kicker and solenoid magnets were used.
The kicker magnet allows each bunch to deflect in different directions and then use the solenoid magnet to cross multiple bunches at the same point in the water depth.
The initial study was to evaluate dose peaks in deep water using a real setup with realistic apertures for the exit window and magnets.

Simulation setup used in FLUKA

- Beam energy: $22\ MeV$
- Beam spot size: $\{0.2, 0.5, 1, 2, 3\}mm$
- Exit window graphite: $510\mu m$



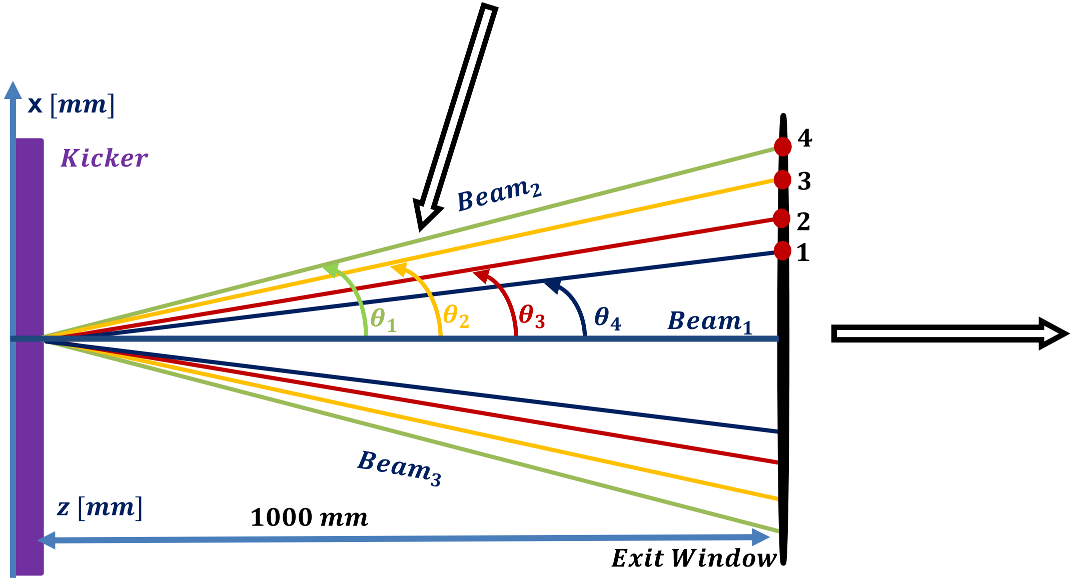
Schematic representation of the electron bunches for the simulation model in the FLUKA code.

SIMULATION SETUP

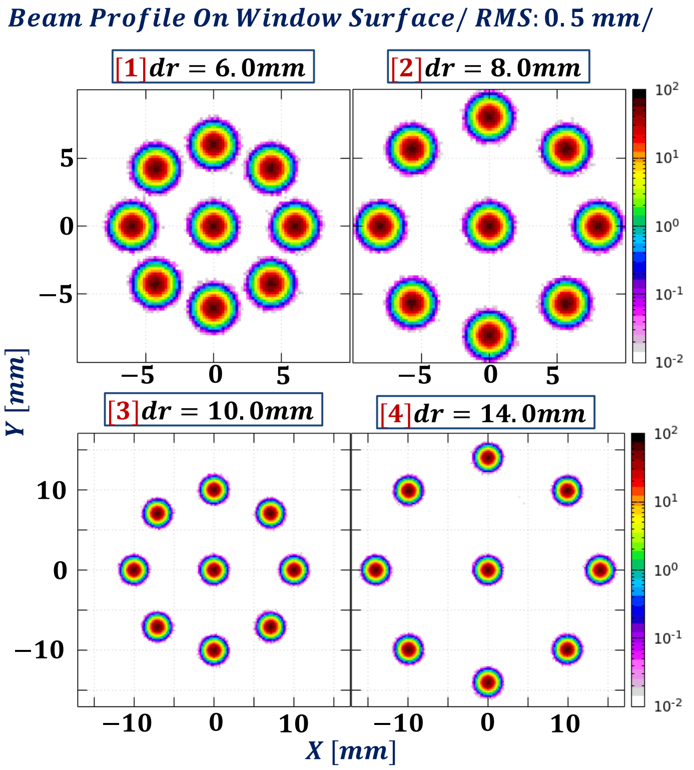
STEP 1: Using a kicker magnet, each bunch is deflected in different direction.

Four cases of different displacements of the bunch after the kicker magnet were investigated.
The displacements angle were

1. $\theta_1 = 6\ mrad$: $[dr = 6.0\ mm]$
2. $\theta_2 = 8\ mrad$: $[dr = 8.0\ mm]$
3. $\theta_3 = 10\ mrad$: $[dr = 10\ mm]$
4. $\theta_4 = 14\ mrad$: $[dr = 14\ mm]$



Schematic representation of the electron bunches for the simulation model in the FLUKA code.



SIMULATION SETUP

STEP 2: Using a solenoid magnet to cross multiple bunches at the same point in the water depth.

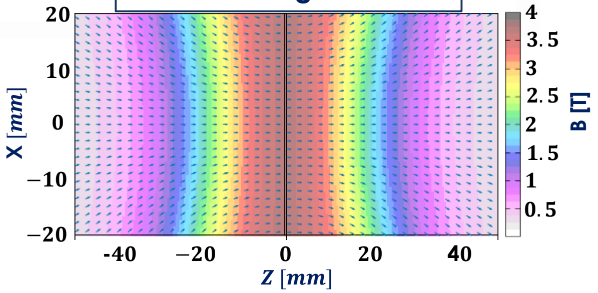
The displacements angle were

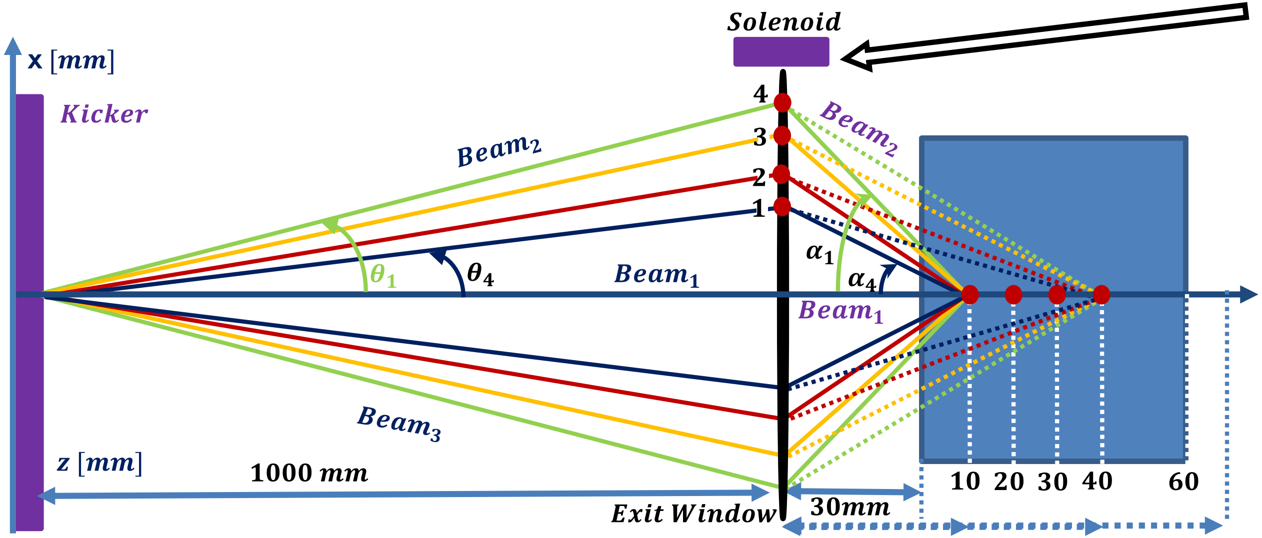
1. $\theta = 6\ mrad$: $[dr = 6\ mm]$
2. $\theta = 8\ mrad$: $[dr = 8\ mm]$
3. $\theta = 10\ mrad$: $[dr = 10\ mm]$
4. $\theta = 14\ mrad$: $[dr = 14\ mm]$

The magnetic field of the solenoid was determined by ASTRA. [L. Xiangkun]

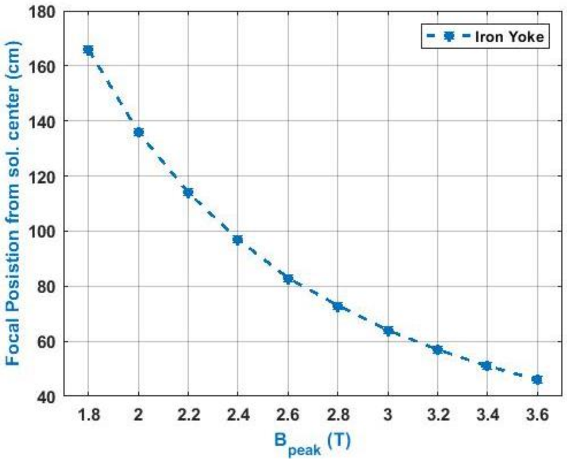
1. $\theta_1 = 6\ mrad$: $z_{min} = 40\ mm \Rightarrow \alpha_{max} = 149\ mrad$ | $z_{max} = 110\ mm \Rightarrow \alpha_{min} = 54\ mrad$
2. $\theta_2 = 8\ mrad$: $z_{min} = 40\ mm \Rightarrow \alpha_{max} = 197\ mrad$ | $z_{max} = 110\ mm \Rightarrow \alpha_{min} = 73\ mrad$
3. $\theta_3 = 10\ mrad$: $z_{min} = 40\ mm \Rightarrow \alpha_{max} = 245\ mrad$ | $z_{max} = 110\ mm \Rightarrow \alpha_{min} = 91\ mrad$
4. $\theta_4 = 14\ mrad$: $z_{min} = 40\ mm \Rightarrow \alpha_{max} = 337\ mrad$ | $z_{max} = 110\ mm \Rightarrow \alpha_{min} = 127\ mrad$

Solenoid magnetic field



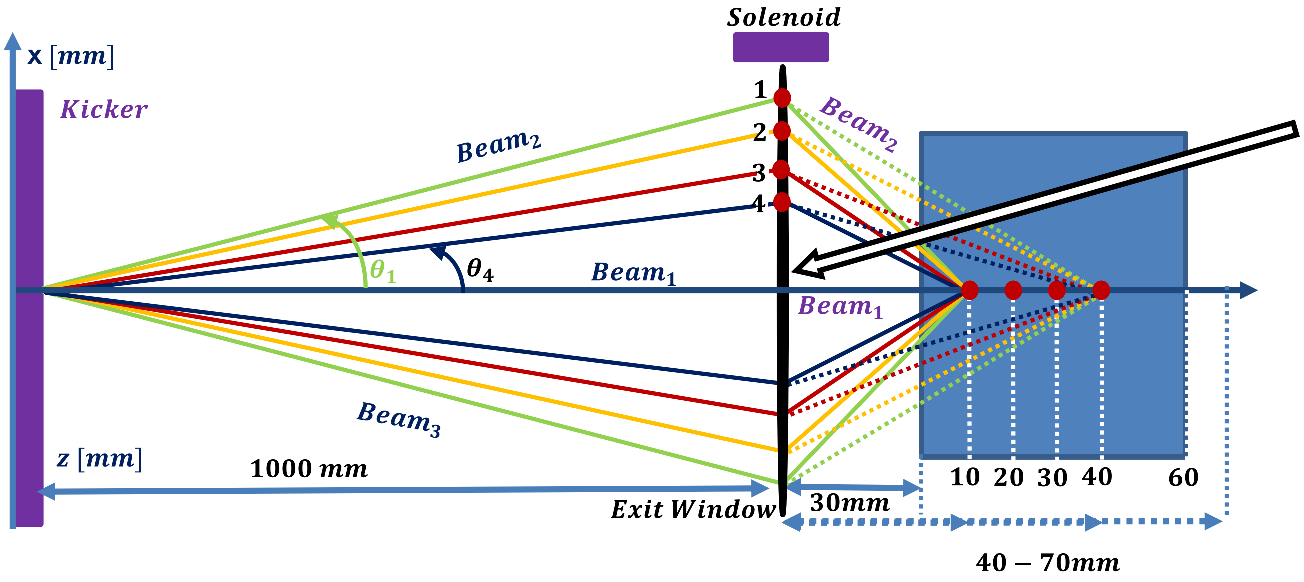


Schematic representation of the electron bunches for the simulation model in the FLUKA code.

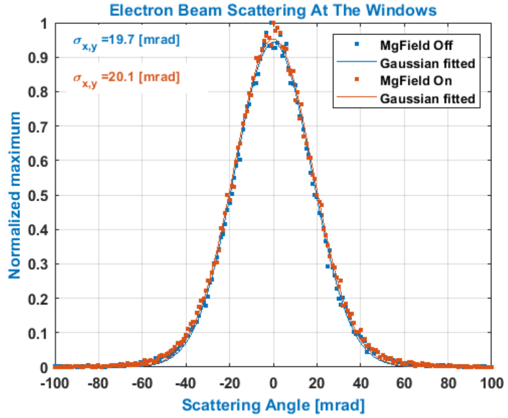


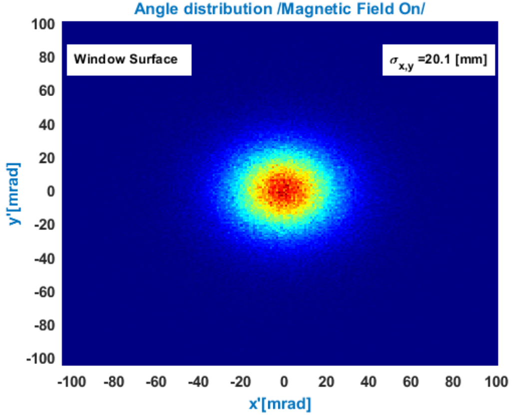
SIMULATION SETUP

Angular distribution of electrons after passing through the exit windows.



Schematic representation of the electron bunches for the simulation model in the FLUKA code.

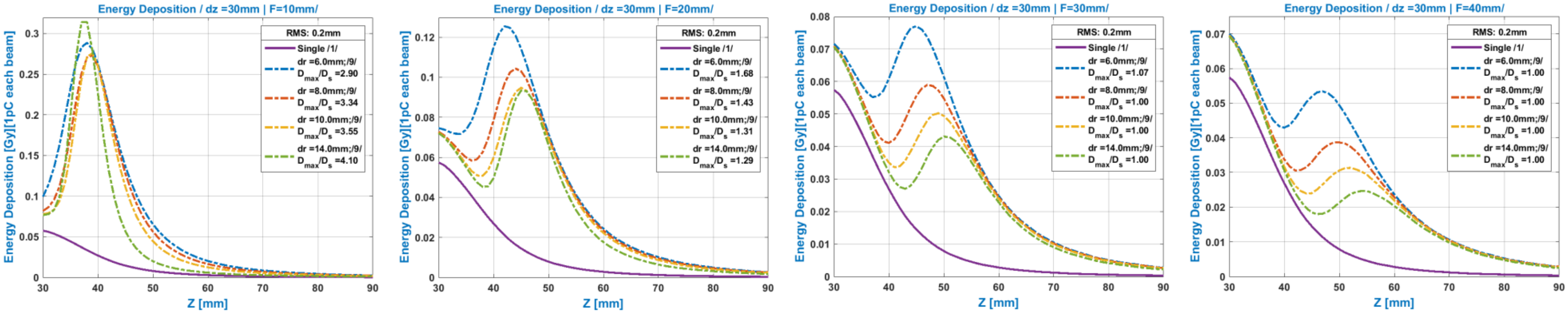




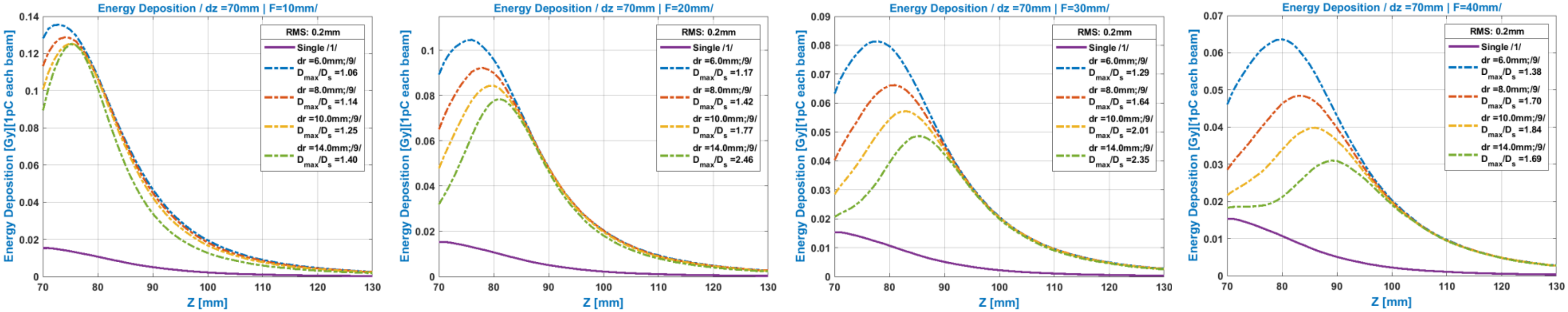
Water: 30mm

ENERGY DEPOSITION ALONG BEAM AXIS

RMS: 0.2 mm



Water: 70mm



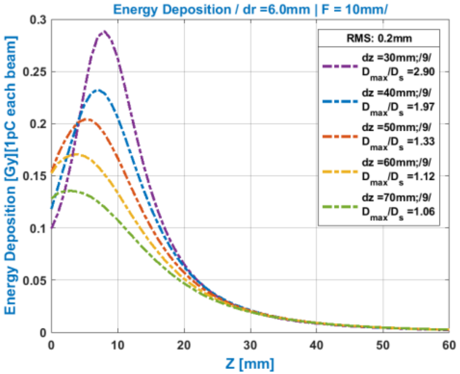
Energy deposition along the beam path where two transverse dimensions are integrated for central $1 \times 1mm^2$ space. The incident beam **RMS is 0.2mm.** The graphs correspond to the cases when the bunches crossing depths after the **water surface** are $10\ mm, 20\ mm, 30\ mm, and\ 40\ mm$. The **top graphs** correspond to the position of the water surface at a distance of $30\ mm$ from the exit window and the **bottom** position of $70\ mm$.

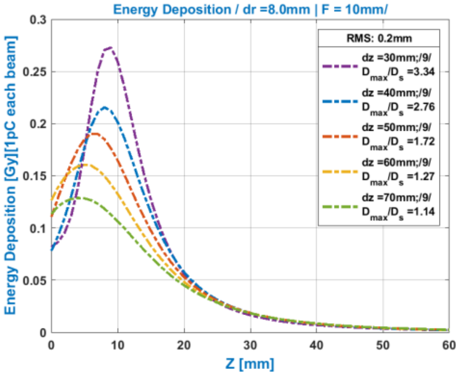
Line colors correspond for different **position of bunches displacement** $dr = 6.0mm, dr = 8.0mm, dr = 10mm, dr = 14mm.$

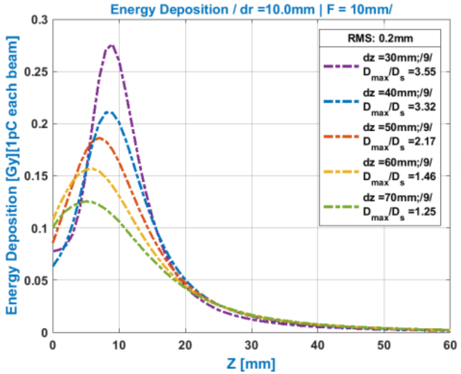
$F: 10mm$

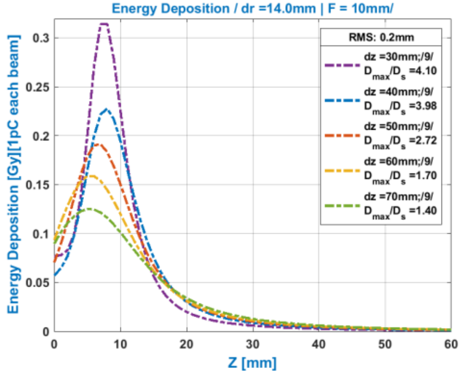
ENERGY DEPOSITION ALONG BEAM AXIS

RMS: 0.2 mm

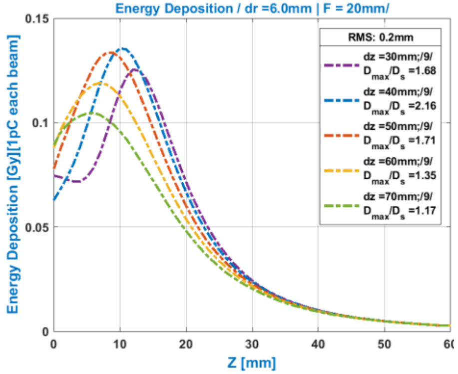


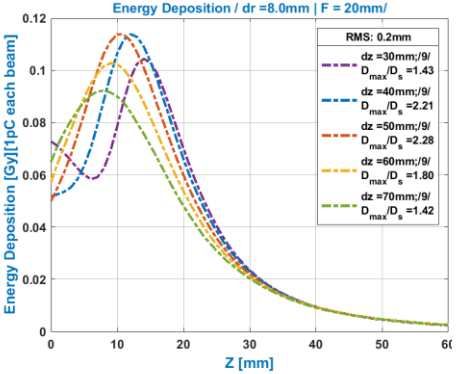


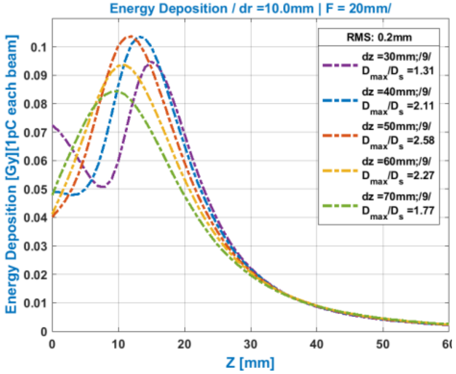


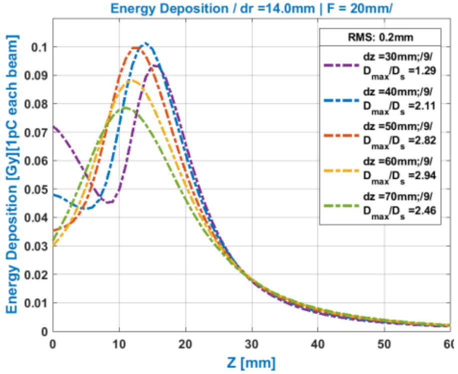


$F: 20mm$









Energy deposition along the beam path where two transverse dimensions are integrated for central $1 \times 1mm^2$ space. The incident beam **RMS is 0.2mm.**

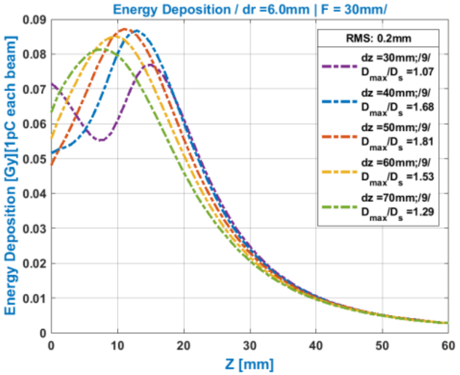
Top plots correspond to **bunches crossing depth $10mm$** and **bottom plots depth $20mm$.**

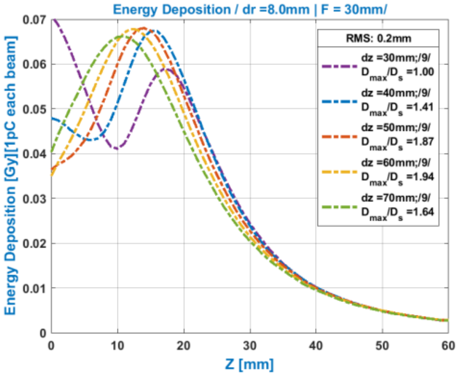
Line colors correspond for different of the **water surface at a distance of $\{30, 40, 50, 60, 70\}\ mm$ from the exit window.**

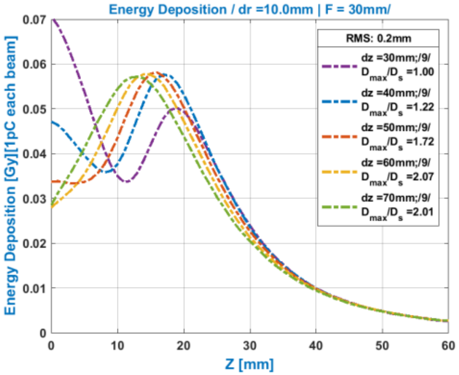
$\boldsymbol{F}: \boldsymbol{30mm}$

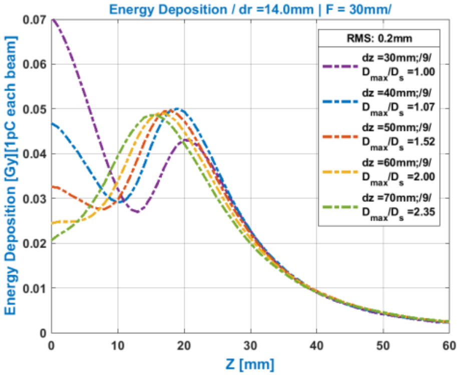
ENERGY DEPOSITION ALONG BEAM AXIS

RMS: 0.2 mm

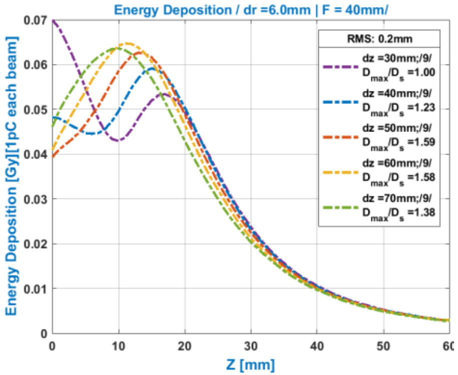


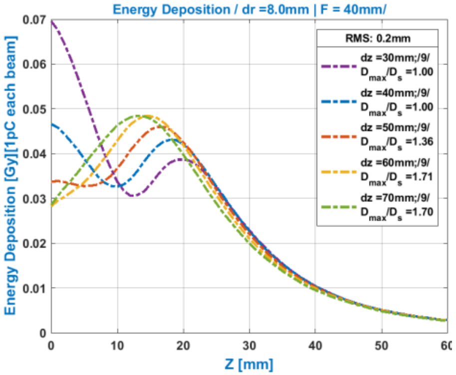


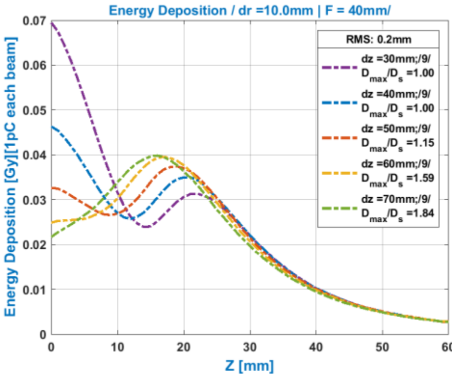


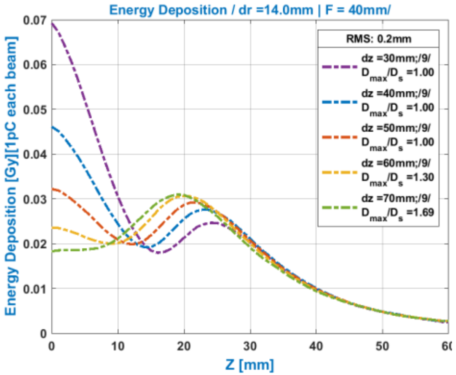


$\boldsymbol{F}: \boldsymbol{40mm}$









Energy deposition along the beam path where two transverse dimensions are integrated for central $\mathbf{1 \times 1mm^2}$ space. The incident beam **RMS is 0.2mm.**

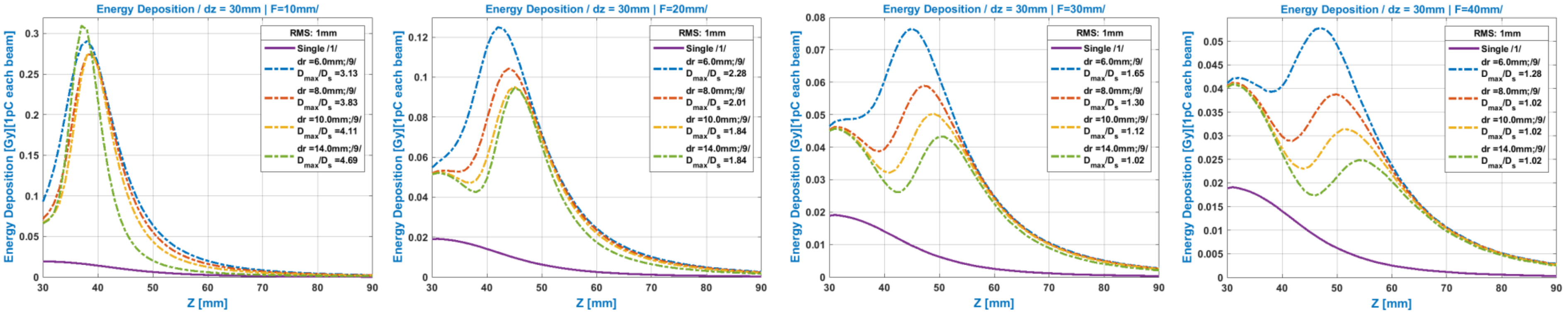
Top plots correspond to **bunches crossing depth $\mathbf{30mm}$** and **bottom plots depth $\mathbf{40mm}$.**

Line colors correspond for different of the **water surface at a distance of $\{30, 40, 50, 60, 70\}\ mm$ from the exit window.**

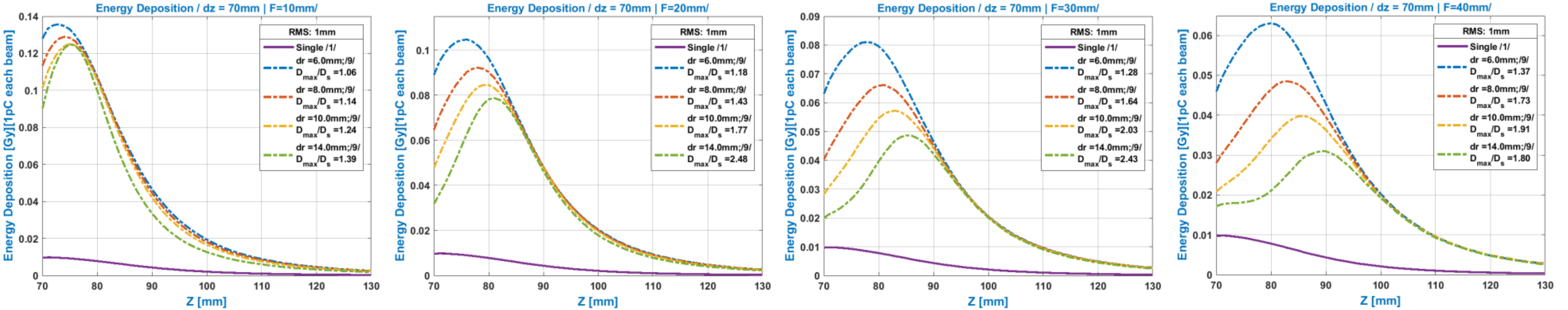
Water: *30mm*

ENERGY DEPOSITION ALONG BEAM AXIS

RMS: 1.0 mm



Water: *70mm*

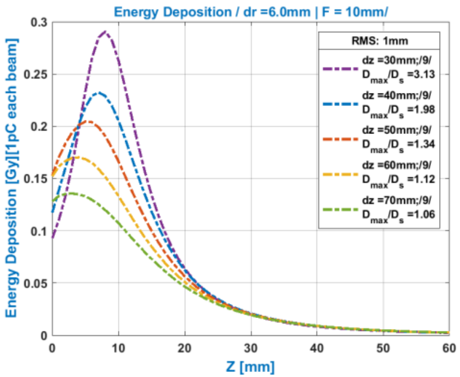


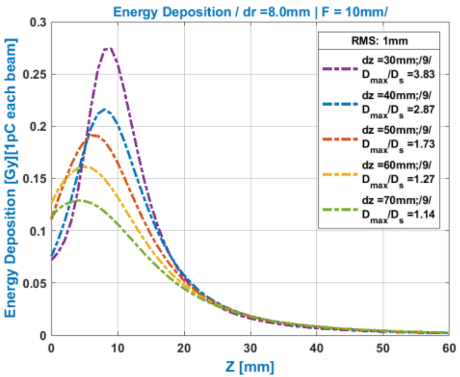
Energy deposition along the beam path where two transverse dimensions are integrated for central $\mathbf{1 \times 1mm^2}$ space. The incident beam **RMS is 1.0mm.** The graphs correspond to the cases when the bunches crossing depths after the **water surface** are $\mathbf{10\ mm, 20\ mm, 30\ mm, and\ 40\ mm}$. The **top graphs** correspond to the position of the water surface at a distance of $\mathbf{30\ mm}$ from the exit window and the **bottom** position of $\mathbf{70\ mm}$.
Line colors correspond for different **position of bunches displacement** $\mathbf{dr = 6.0mm, dr = 8.0mm, dr = 10mm, dr = 14mm.}$

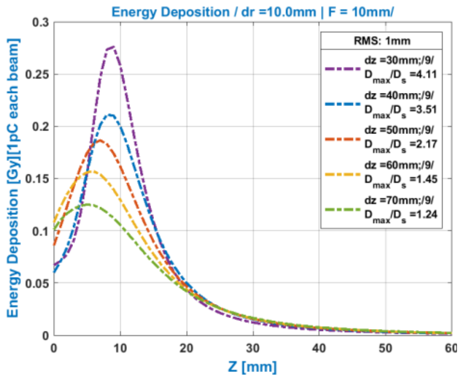
ENERGY DEPOSITION ALONG BEAM AXIS

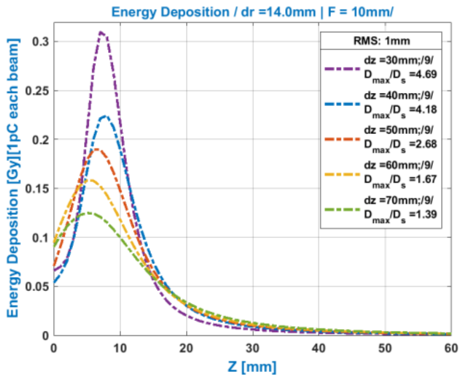
RMS: 1.0 mm

$F: 10mm$

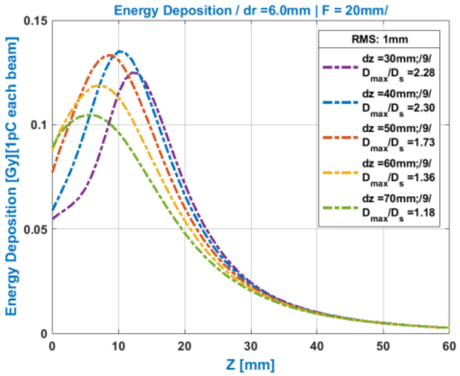


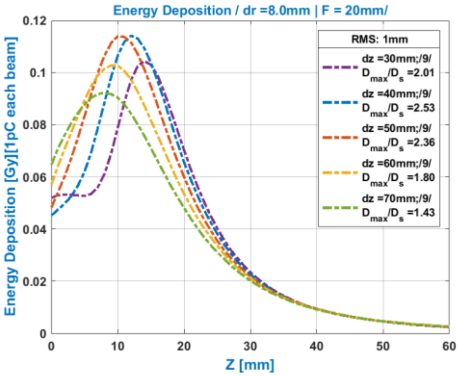


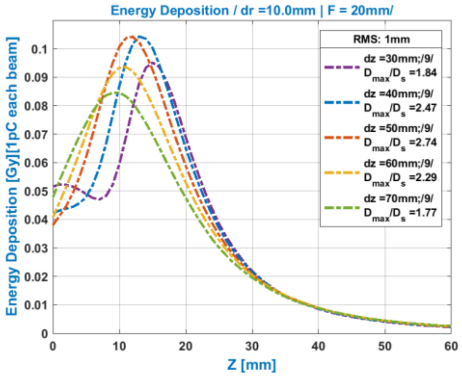


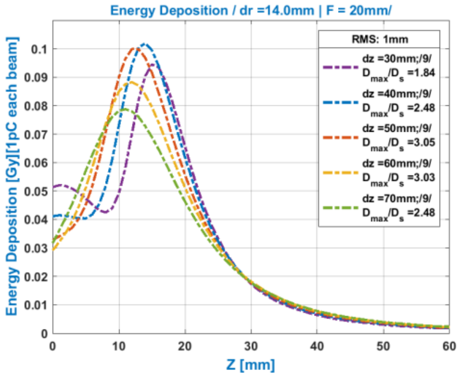


$F: 20mm$









Energy deposition along the beam path where two transverse dimensions are integrated for central $1 \times 1mm^2$ space. The incident beam **RMS is 1.0 mm.**

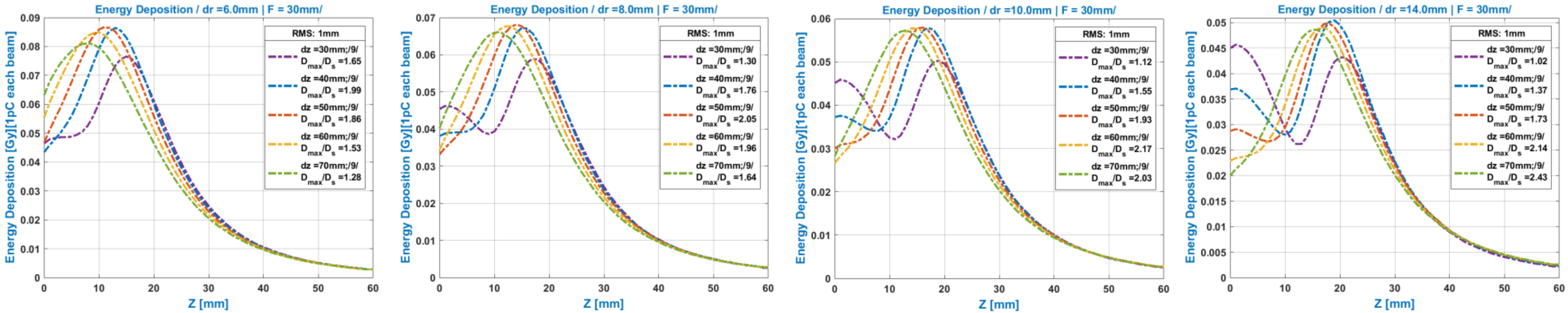
Top plots correspond to **bunches crossing depth $10mm$** and **bottom plots depth $20mm$.**

Line colors correspond for different of the **water surface at a distance of $\{30, 40, 50, 60, 70\}$ mm from the exit window.**

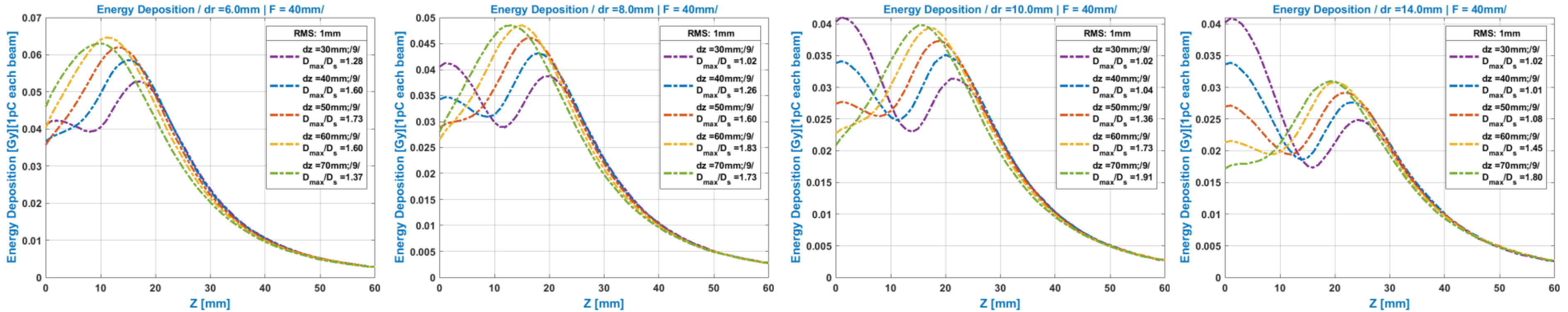
$F: 30mm$

ENERGY DEPOSITION ALONG BEAM AXIS

RMS: 1.0 mm



$F: 40mm$



Energy deposition along the beam path where two transverse dimensions are integrated for central $\mathbf{1 \times 1mm^2}$ space. The incident beam **RMS is 1.0mm.**

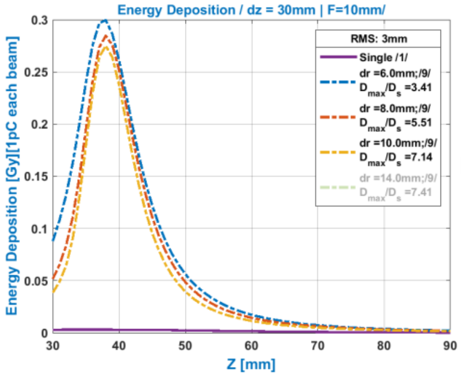
Top plots correspond to **bunches crossing depth $30mm$** and **bottom plots depth $40mm$.**

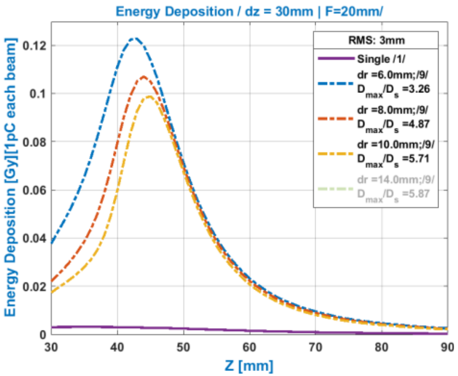
Line colors correspond for different of the **water surface at a distance of $\{30, 40, 50, 60, 70\}\ mm$ from the exit window.**

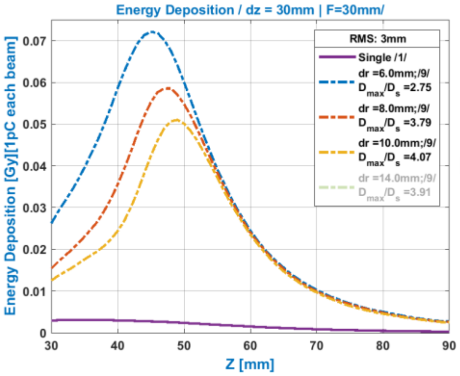
ENERGY DEPOSITION ALONG BEAM AXIS

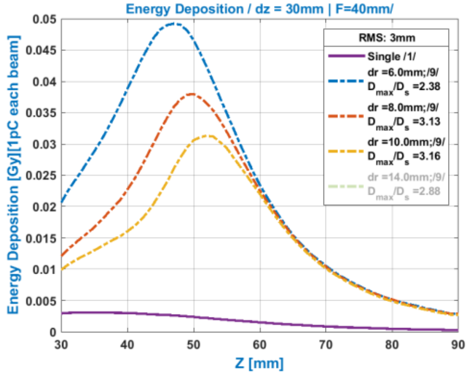
RMS: 3.0 mm

Water*: 30*mm

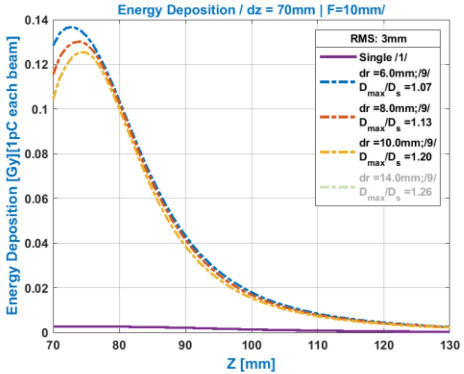


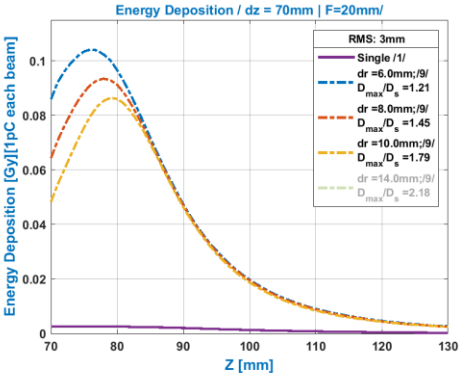


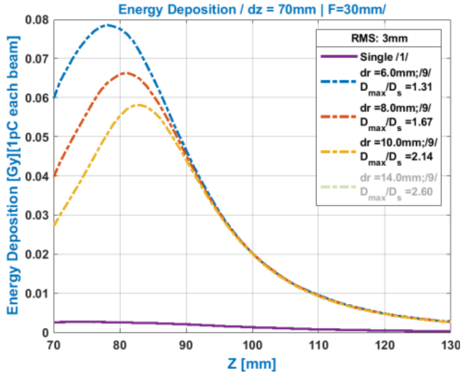


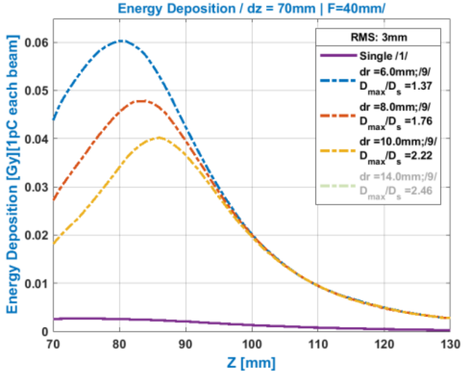


Water*: 70*mm







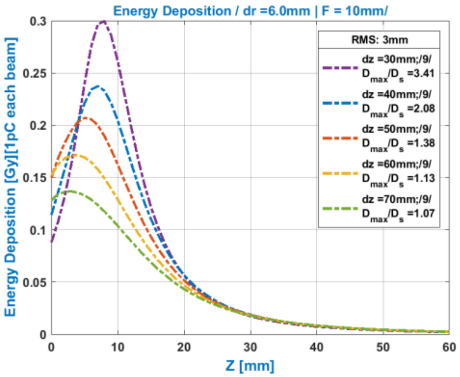


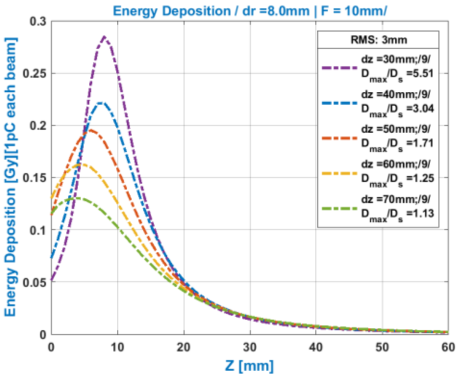
Energy deposition along the beam path where two transverse dimensions are integrated for central $\mathbf{1 \times 1mm^2}$ space. The incident beam **RMS is 3.0mm.** The graphs correspond to the cases when the bunches crossing depths after the **water surface** are $\mathbf{10\ mm, 20\ mm, 30\ mm, and\ 40\ mm}$. The **top graphs** correspond to the position of the water surface at a distance of $\mathbf{30\ mm}$ from the exit window and the **bottom** position of $\mathbf{70\ mm}$.
Line colors correspond for different **position of bunches displacement** $\mathbf{dr = 6.0mm, dr = 8.0mm, dr = 10mm.}$

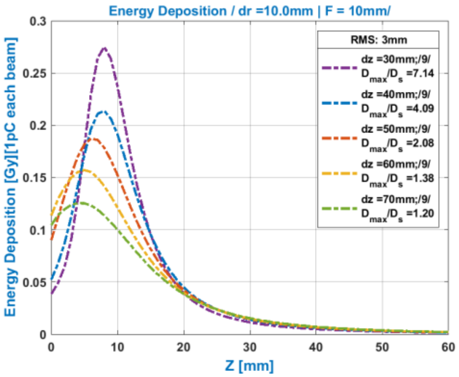
ENERGY DEPOSITION ALONG BEAM AXIS

RMS: 3.0 mm

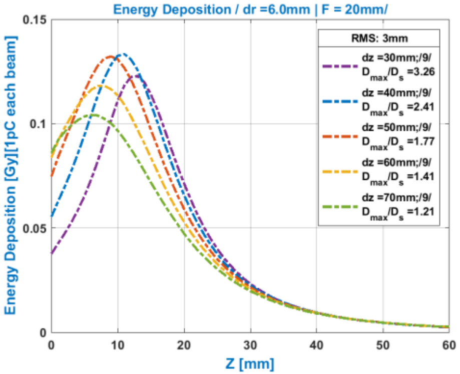
$\boldsymbol{F}: \mathbf{10}\boldsymbol{mm}$

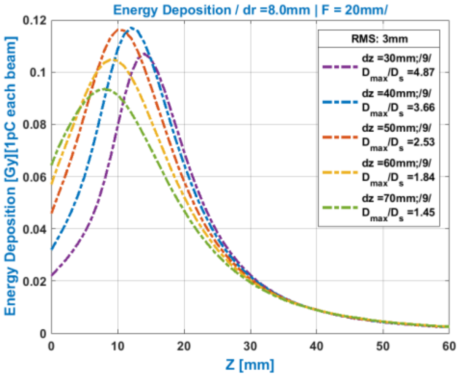


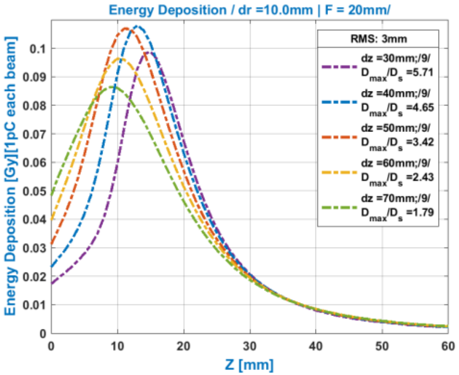




$\boldsymbol{F}: \mathbf{20}\boldsymbol{mm}$







Energy deposition along the beam path where two transverse dimensions are integrated for central $\mathbf{1} \times \mathbf{1}\boldsymbol{mm}^{\mathbf{2}}$ space. The incident beam **RMS is 3.0 mm.**

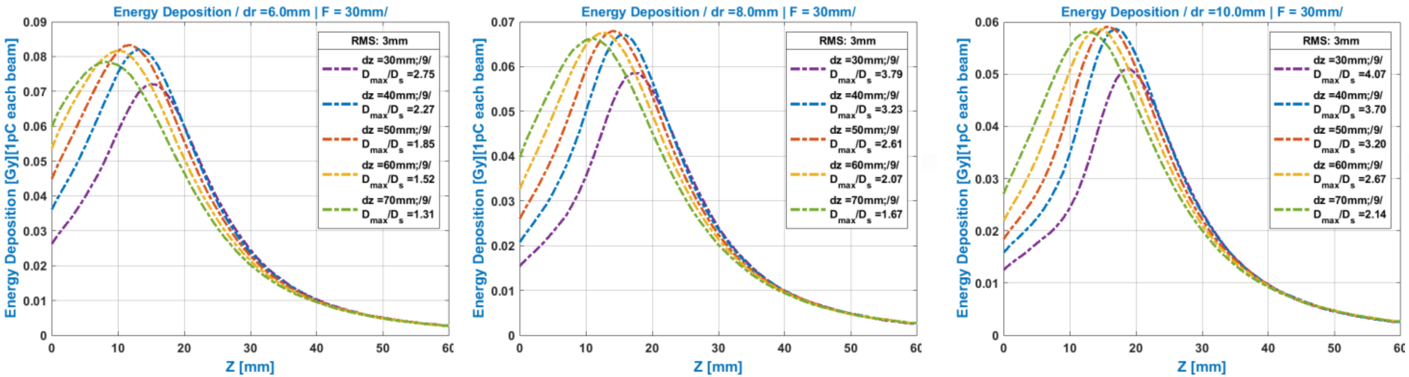
Top plots correspond to **bunches crossing depth $\mathbf{10}\boldsymbol{mm}$** and **bottom plots depth $\mathbf{20}\boldsymbol{mm}$.**

Line colors correspond for different of the **water surface at a distance of $\{\mathbf{30}, \mathbf{40}, \mathbf{50}, \mathbf{60}, \mathbf{70}\}\ \boldsymbol{mm}$ from the exit window.**

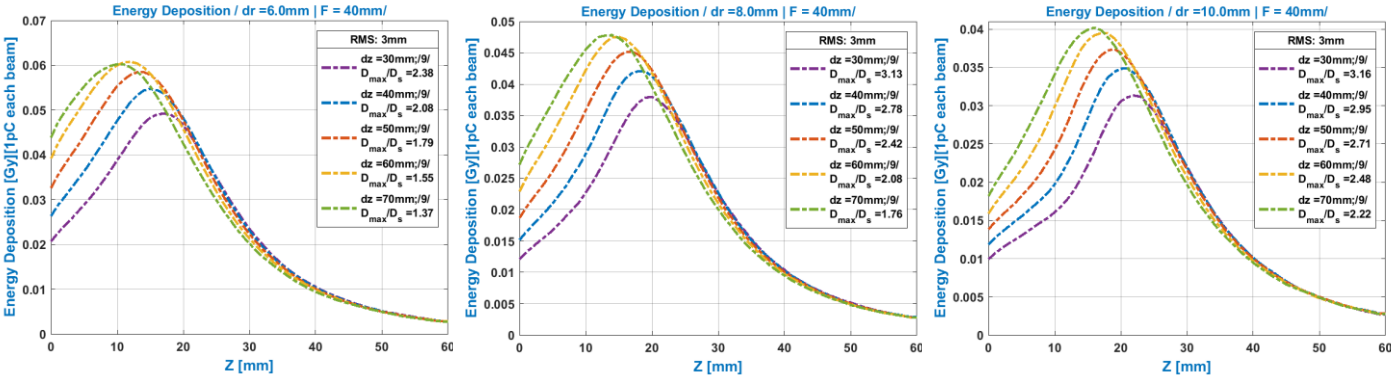
ENERGY DEPOSITION ALONG BEAM AXIS

RMS: 3.0 mm

F*: 30*mm



F*: 40*mm



Energy deposition along the beam path where two transverse dimensions are integrated for central $\mathbf{1 \times 1mm^2}$ space. The incident beam **RMS is 3.0mm.**

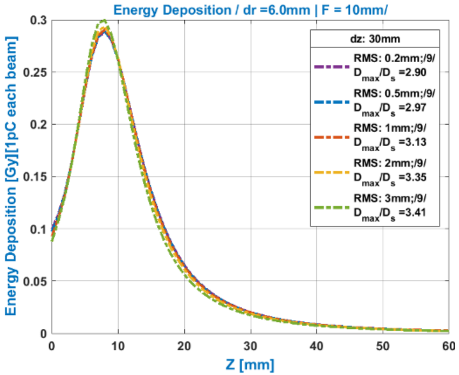
Top plots correspond to **bunches crossing depth $\mathbf{30mm}$** and **bottom plots depth $\mathbf{40mm}$.**

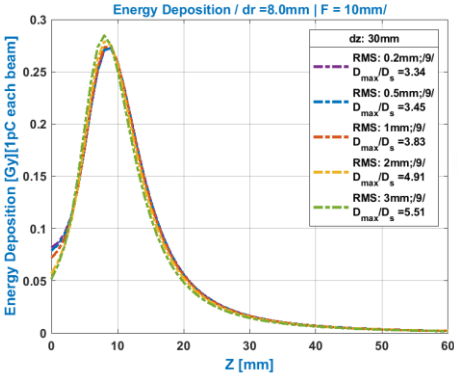
Line colors correspond for different of the **water surface at a distance of $\mathbf{\{30, 40, 50, 60, 70\}\ mm}$ from the exit window.**

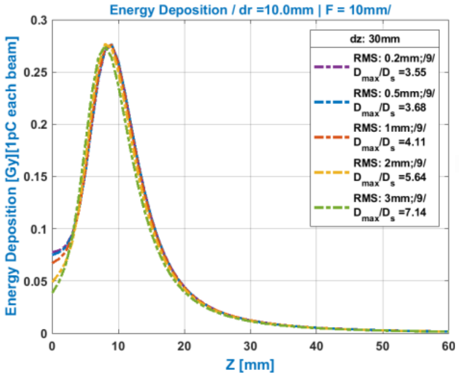
dz: 30 mm

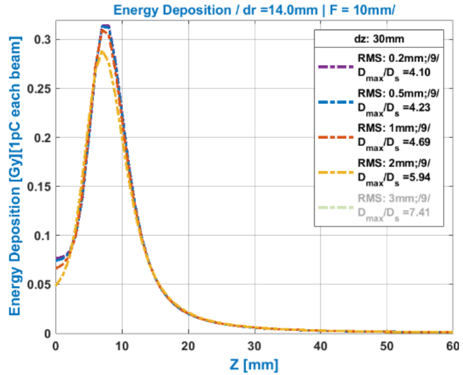
ENERGY DEPOSITION ALONG BEAM AXIS

$\boldsymbol{F: 10mm}$

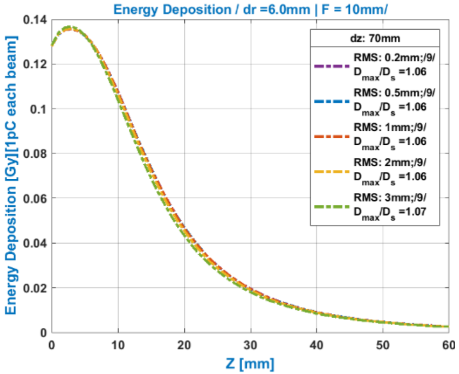


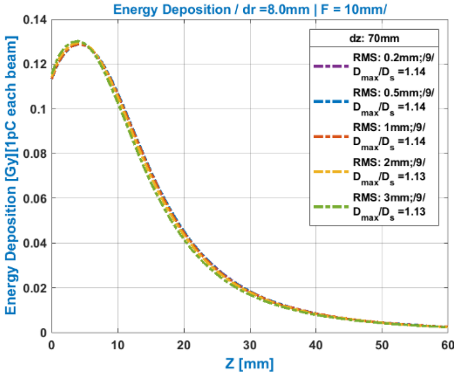


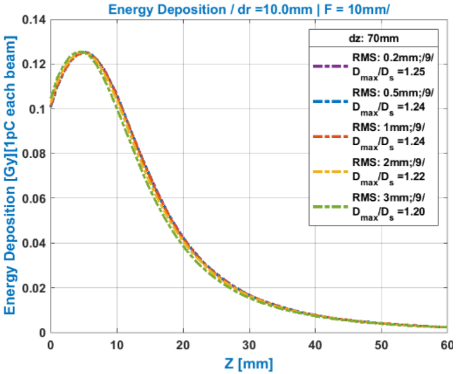


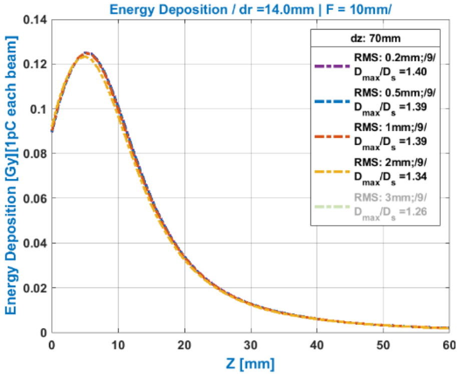


dz: 70 mm





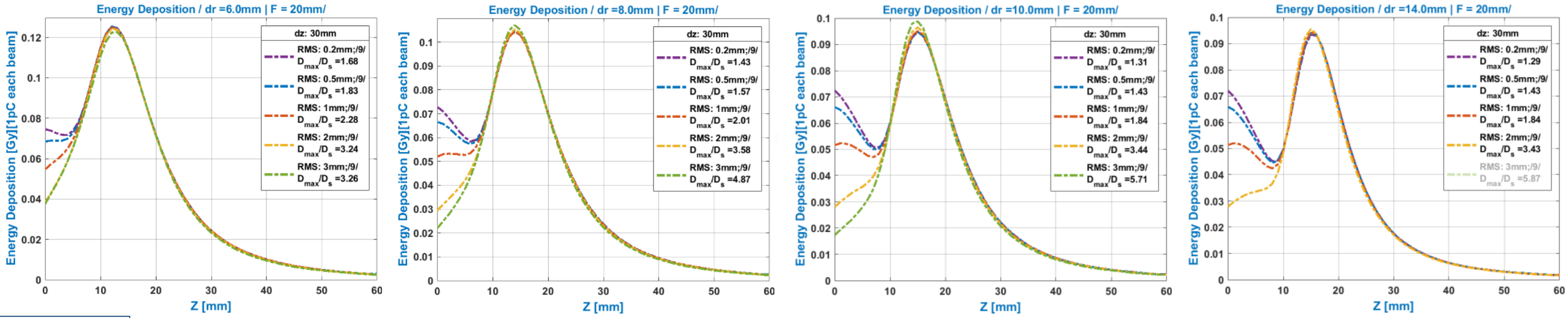




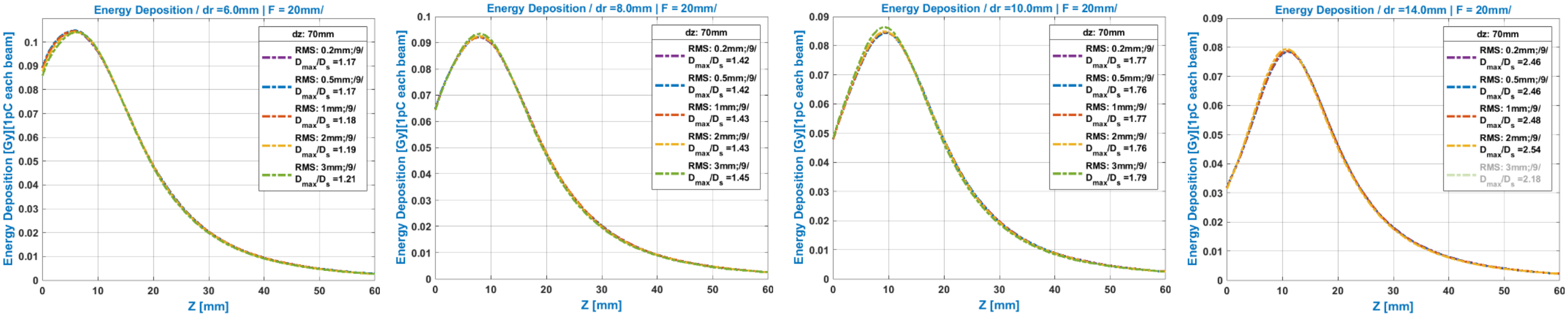
The graphs show the distribution of the energy deposition along the center of the water for various **RMS** beam sizes when the bunches crossing depths after the **water surface** of $\mathbf{10\ mm}$.
Line colors correspond to different **RMS** beam sizes. The **top graphs** correspond to the position of the **water surface** at a distance of $\mathbf{30\ mm}$ from the exit window and the **bottom** position of $\mathbf{70\ mm}$.

ENERGY DEPOSITION ALONG BEAM AXIS

$F: 20mm$



dz: 70 mm



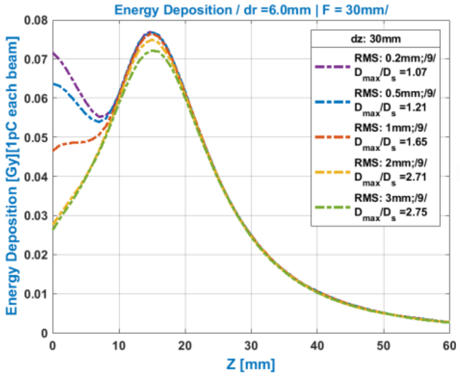
The graphs show the distribution of the energy deposition along the center of the water for various **RMS** beam sizes when the bunches crossing depths after the **water surface** of $20\ mm$.

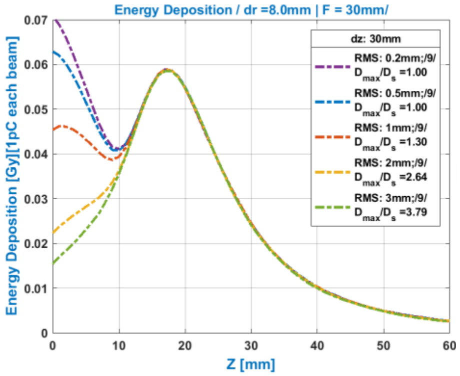
Line colors correspond to different **RMS** beam sizes. The **top graphs** correspond to the position of the **water surface** at a distance of $30\ mm$ from the exit window and the **bottom** position of $70\ mm$.

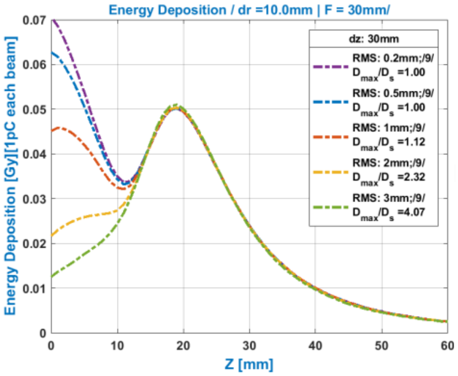
dz: 30 mm

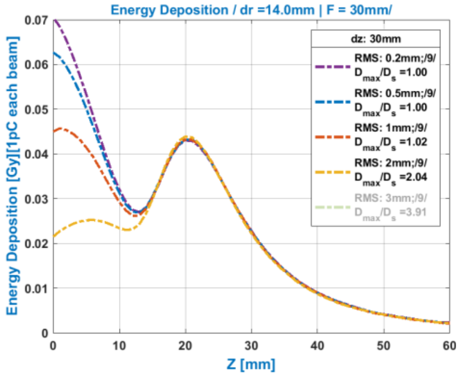
ENERGY DEPOSITION ALONG BEAM AXIS

$F: 30mm$

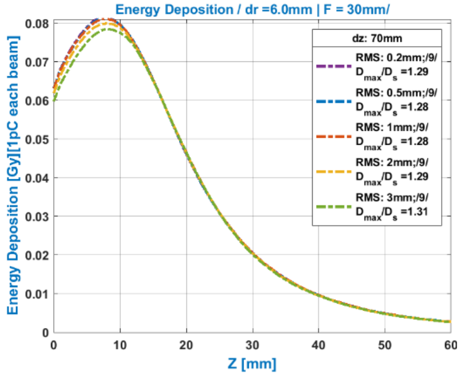


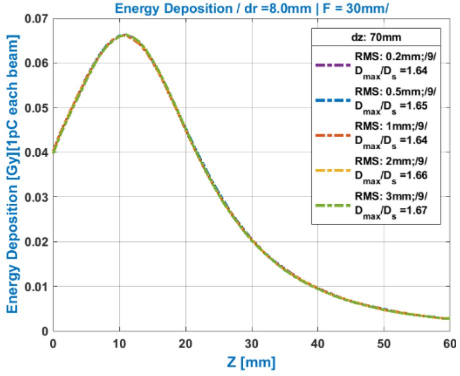


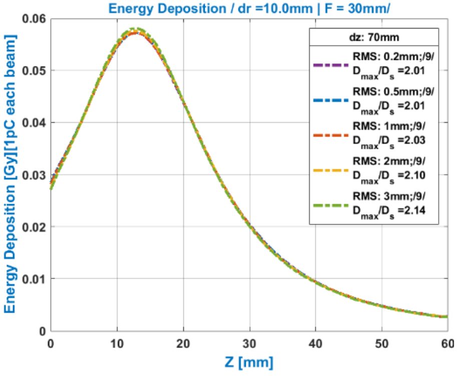


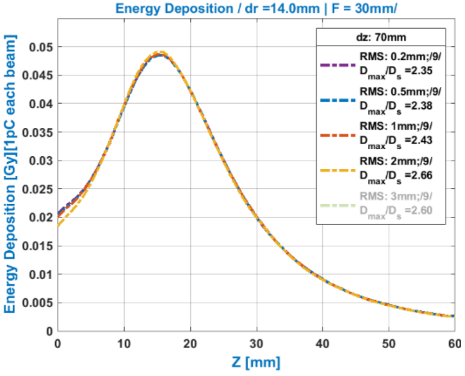


dz: 70 mm









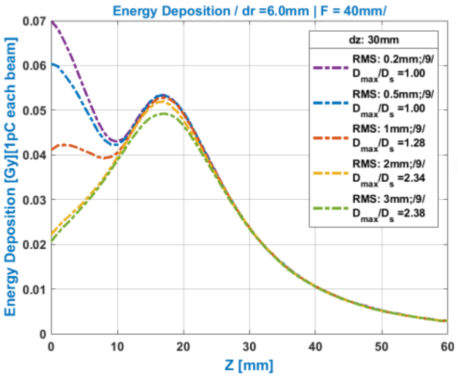
The graphs show the distribution of the energy deposition along the center of the water for various **RMS** beam sizes when the bunches crossing depths after the **water surface** of $30\, mm$.

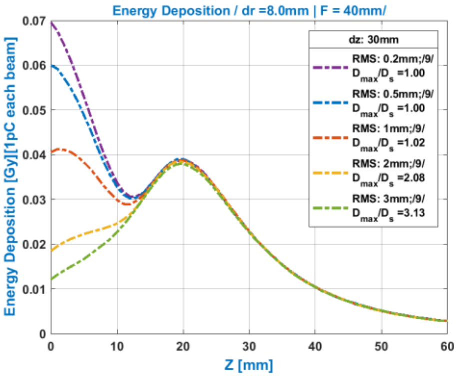
Line colors correspond to different **RMS** beam sizes. The **top graphs** correspond to the position of the **water surface** at a distance of $30\, mm$ from the exit window and the **bottom** position of $70\, mm$.

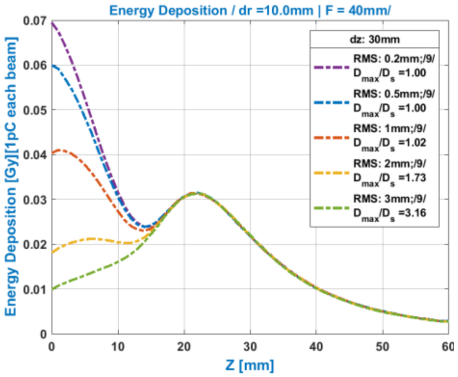
ENERGY DEPOSITION ALONG BEAM AXIS

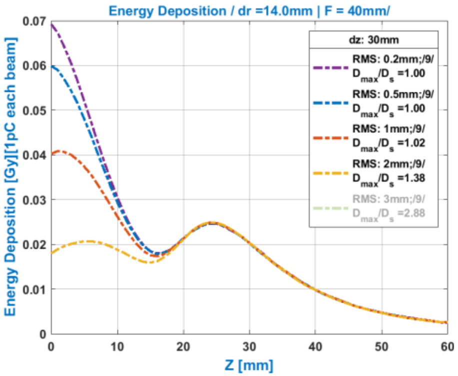
dz: 30 mm

F*: 40*mm

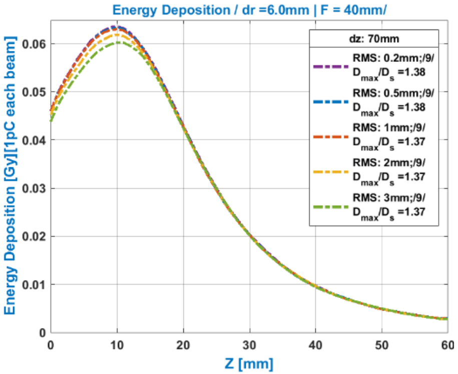


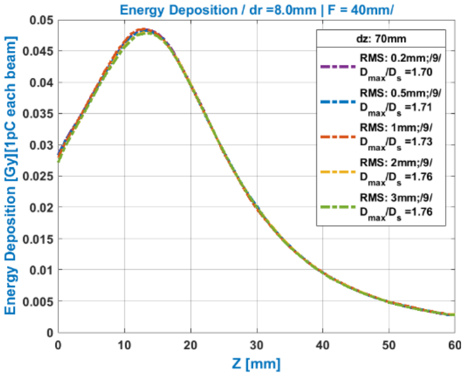


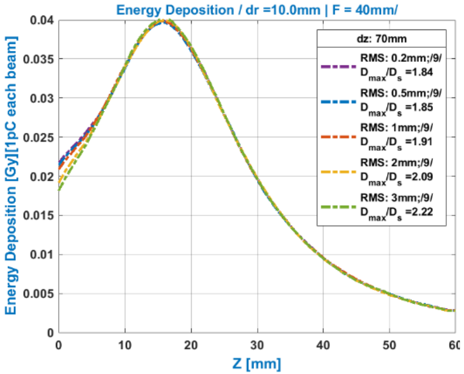


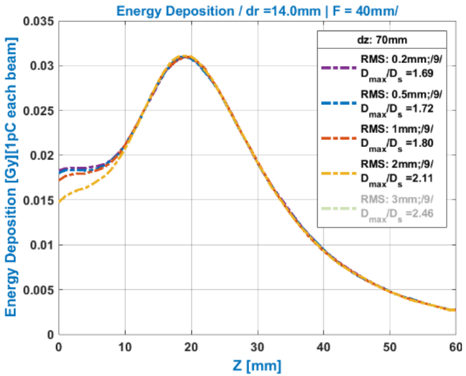


dz: 70 mm









The graphs show the distribution of the energy deposition along the center of the water for various **RMS** beam sizes when the bunches crossing depths after the **water surface** of $40\ mm$.

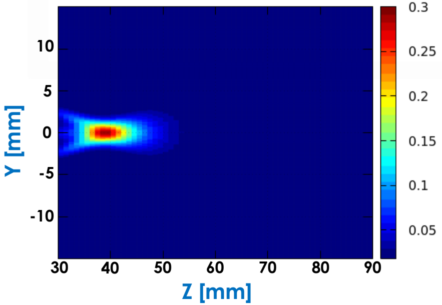
Line colors correspond to different **RMS** beam sizes. The **top graphs** correspond to the position of the **water surface** at a distance of $30\ mm$ from the exit window and the **bottom** position of $70\ mm$.

$dz = 30\ mm$

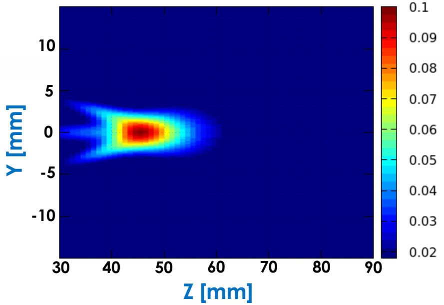
ENERGY DEPOSITION ALONG BEAM AXIS

$RMS: 2\ mm$

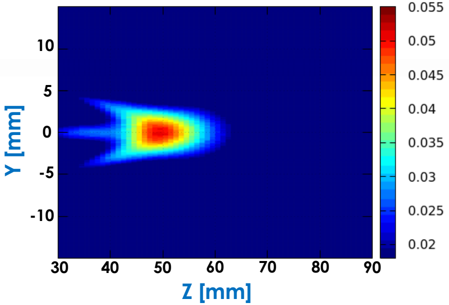
$F = 10\ mm\ /\ dr\ = 10\ mm$



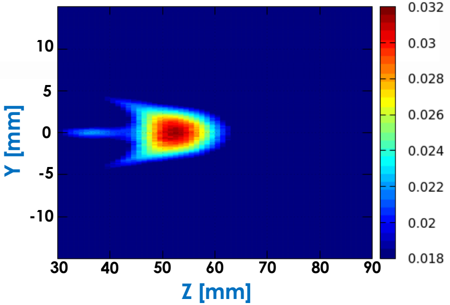
$F = 20\ mm\ /\ dr\ = 10\ mm$



$F = 30\ mm\ /\ dr\ = 10\ mm$

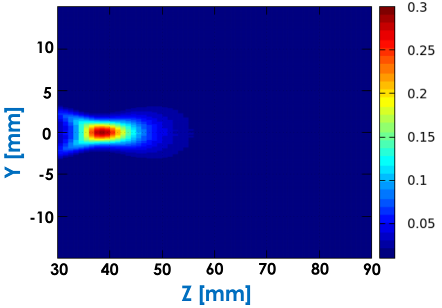


$F = 40\ mm\ /\ dr\ = 10\ mm$

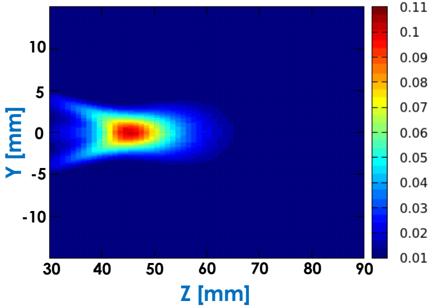


$RMS: 3\ mm$

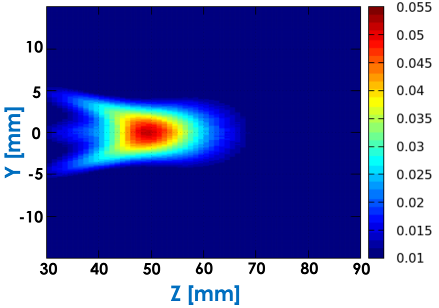
$F = 10\ mm\ /\ dr\ = 10\ mm$



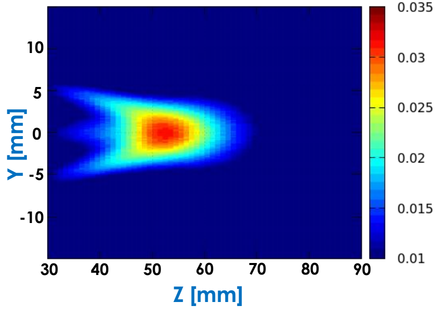
$F = 20\ mm\ /\ dr\ = 10\ mm$



$F = 30\ mm\ /\ dr\ = 10\ mm$



$F = 40\ mm\ /\ dr\ = 10\ mm$



The energy deposition distribution in **YZ** plane along the incident electrons. The energy deposition is integral over vertical axis **1mm** central slice.

CONCLUSION

- **The results of simulations for intersection of several bunches at one point at some depth.**
  - **By the kicker and solenoid magnets, it is possible to increase the peak dose in the depth of water.**
  - **Variation of bunches crossing depth allows controlling the deepness of the peak.**
  - **it is possible to have a peak in the depth ~ 7 times higher than the dose in the water surface.**
  - **Using the different beam RMS it is possible to control the area of homogeneous dose in the depth (~25mm).**
  - **In the case of big RMS, it is possible to control the position and value of dose peak, and damage of exit window is minimal.**

Thank you for your attention