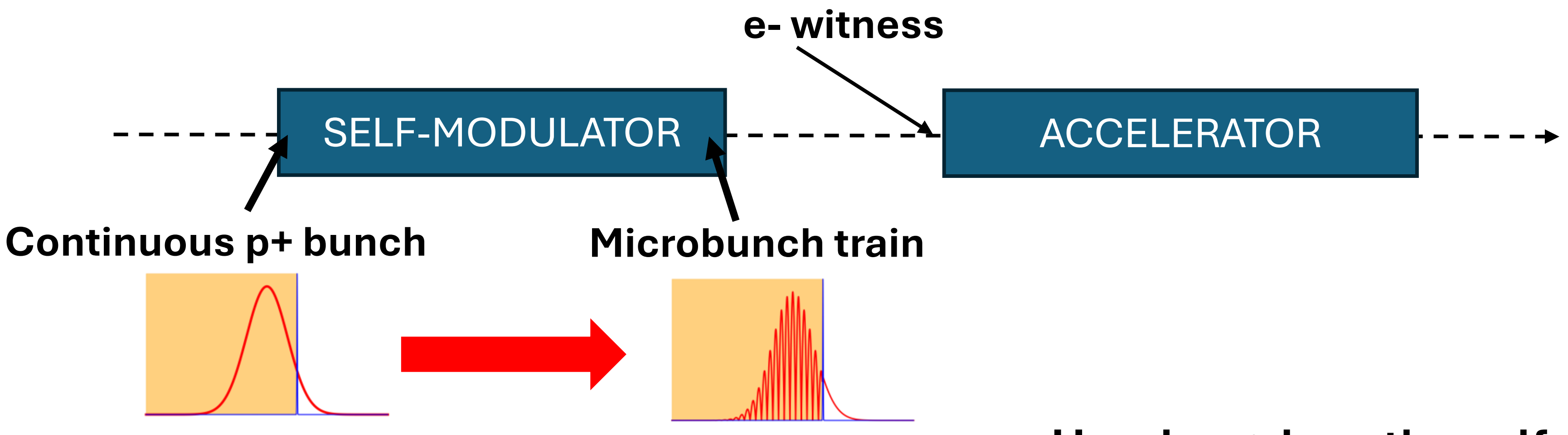
Measurement of SM growth from radius of beam halo

Arthur CLAIREMBAUD

Motivation



How long does the self-modulator need to be in Run 2c?

Two plasmas in **Run 2c**:

- One to **self-modulate** the drive bunch
- One to **accelerate** electrons

Requirement: length of self-modulator needs to be longer than the **saturation length of SM**

→ **Measuring the saturation length of SM**

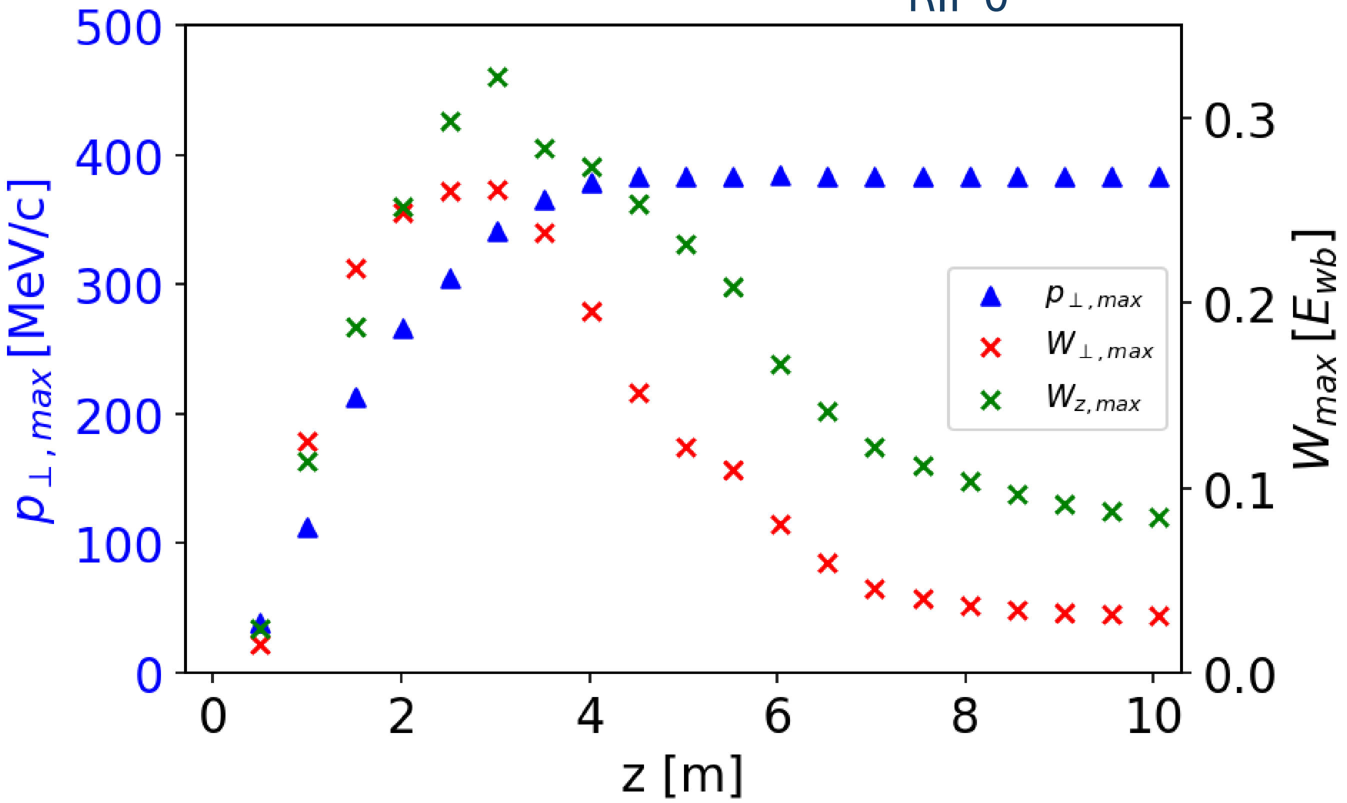
Evolution of wakefields along the plasma

LCODE simulations

As **SM develops**, fields :

- **Grow along the plasma**
  - Microbunch train forms and resonantly excites wakefields
- **Saturate**
  - Microbunch train is fully formed
- **Decay***
  - SM continues to develop
  - Phase of wakefields continues to shift wrt seed, the microbunch train is defocused and the amount of charge on axis decreases

$N_b = 3 \times 10^{11}$
$n_{pe} = 7 \times 10^{14}$/cc
RIF 0



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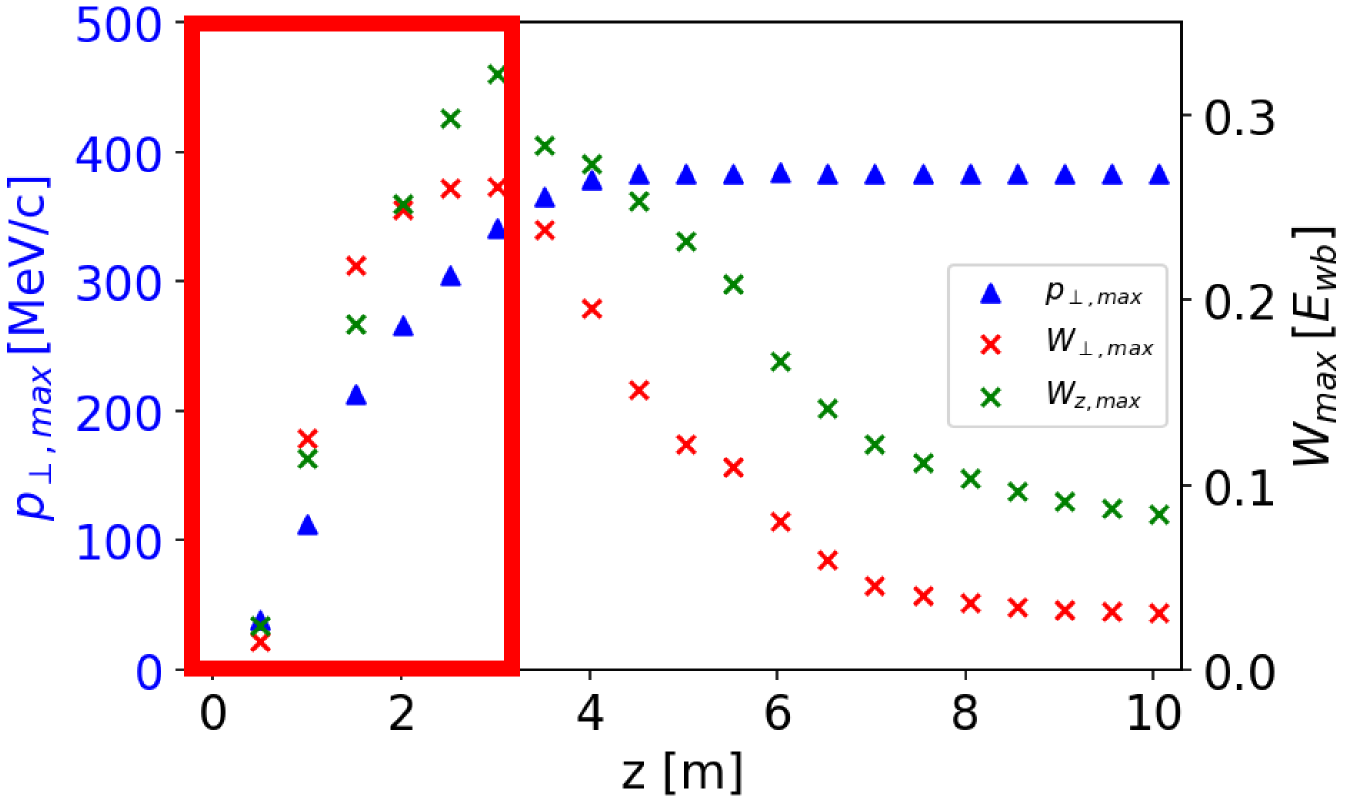

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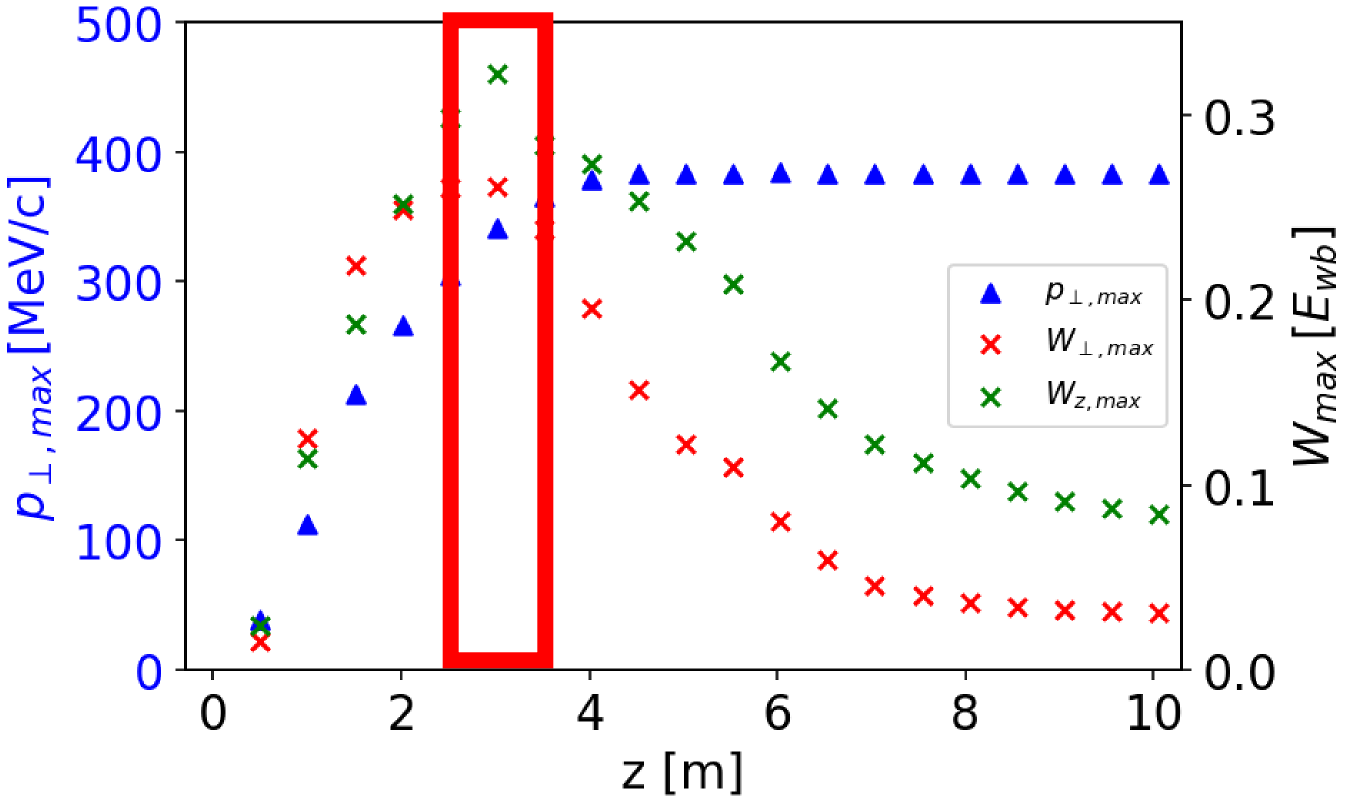

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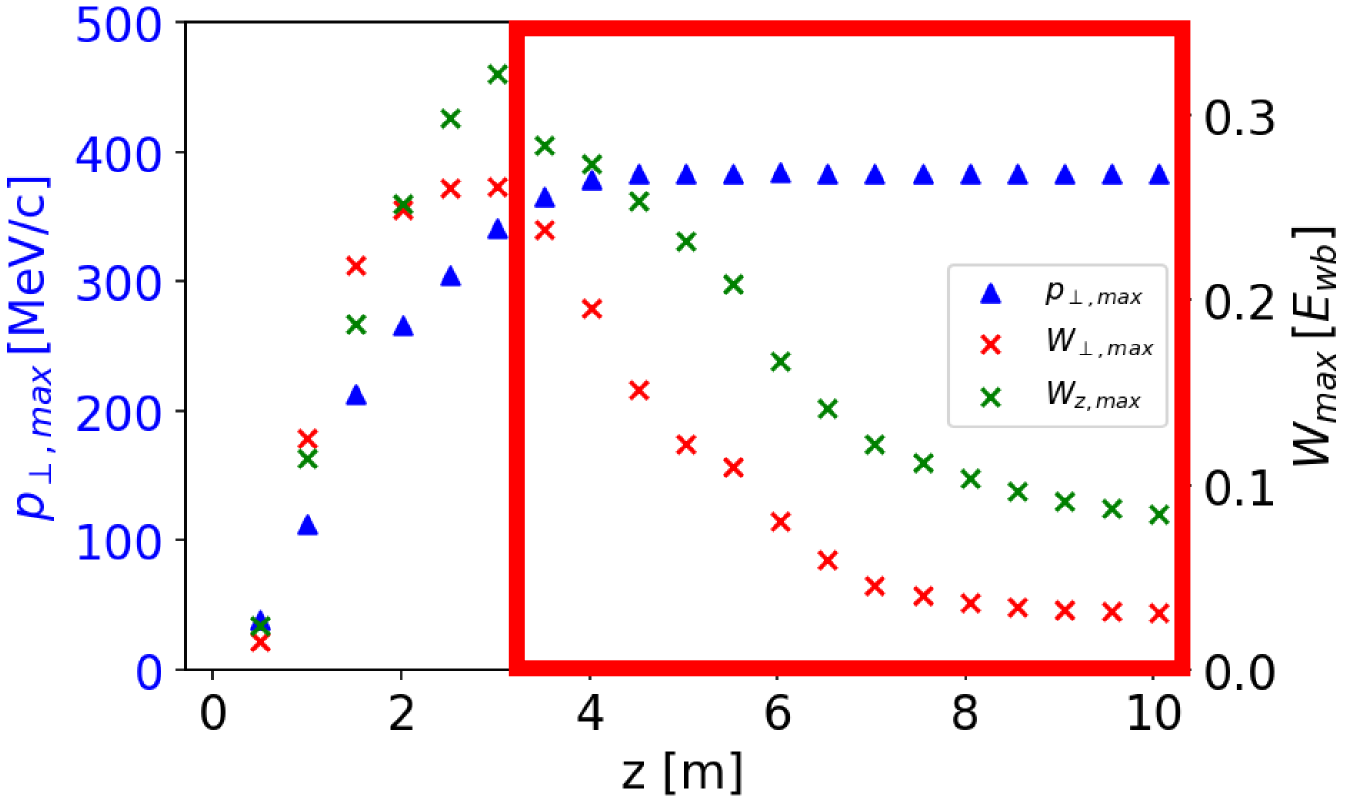
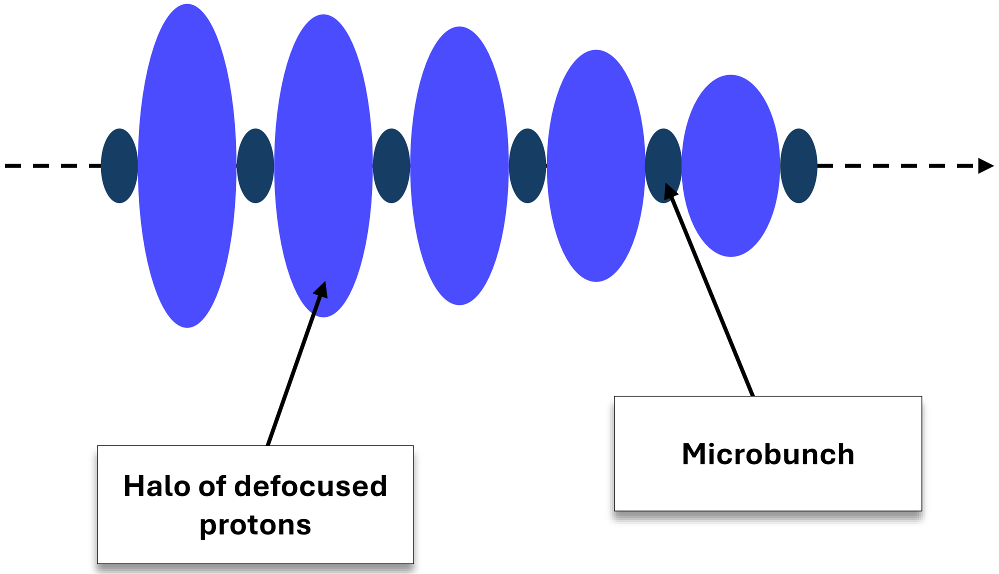


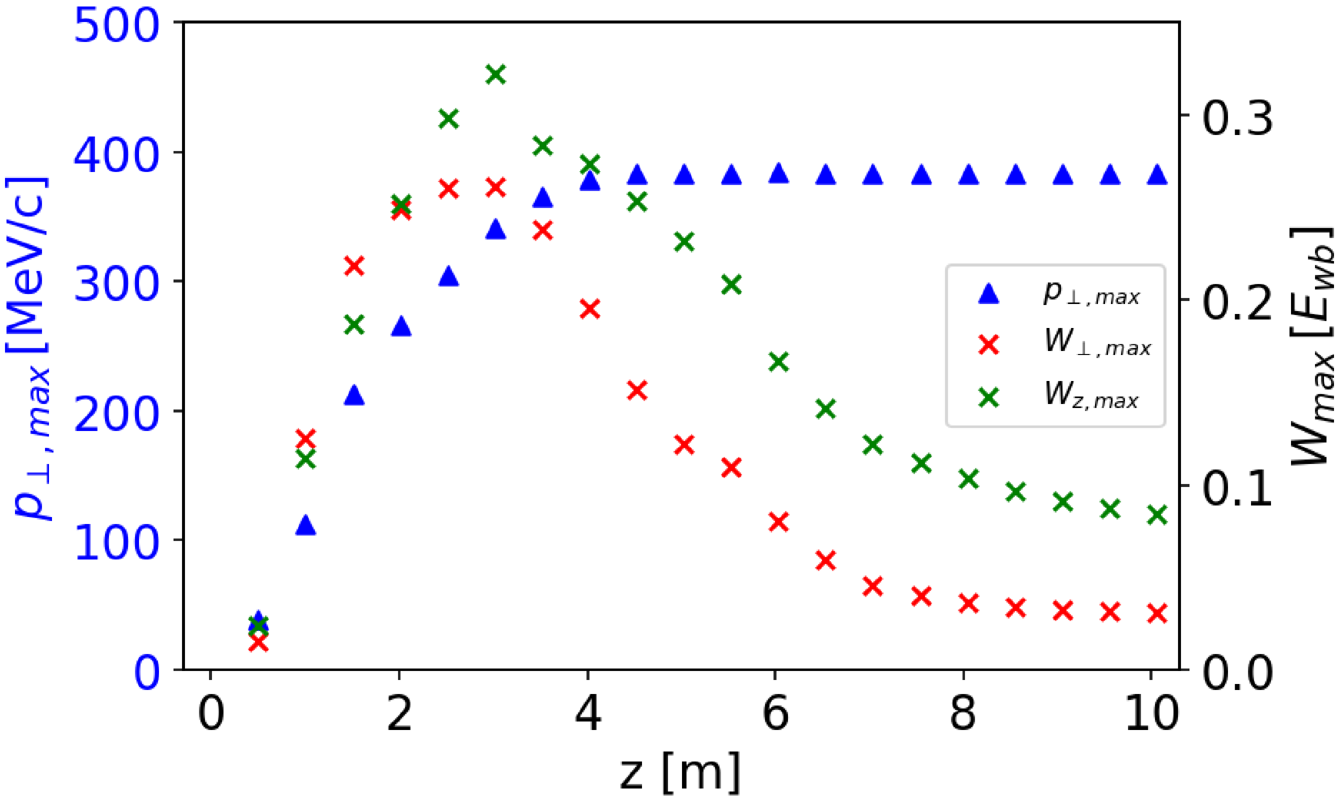
Microbunch train formation ➔ Halo formation

LCODE simulations

Because **SM is a transverse process** :

- Formation of **microbunch train** implies formation of **halo of defocused particles**





Microbunch train formation ➔ Halo formation

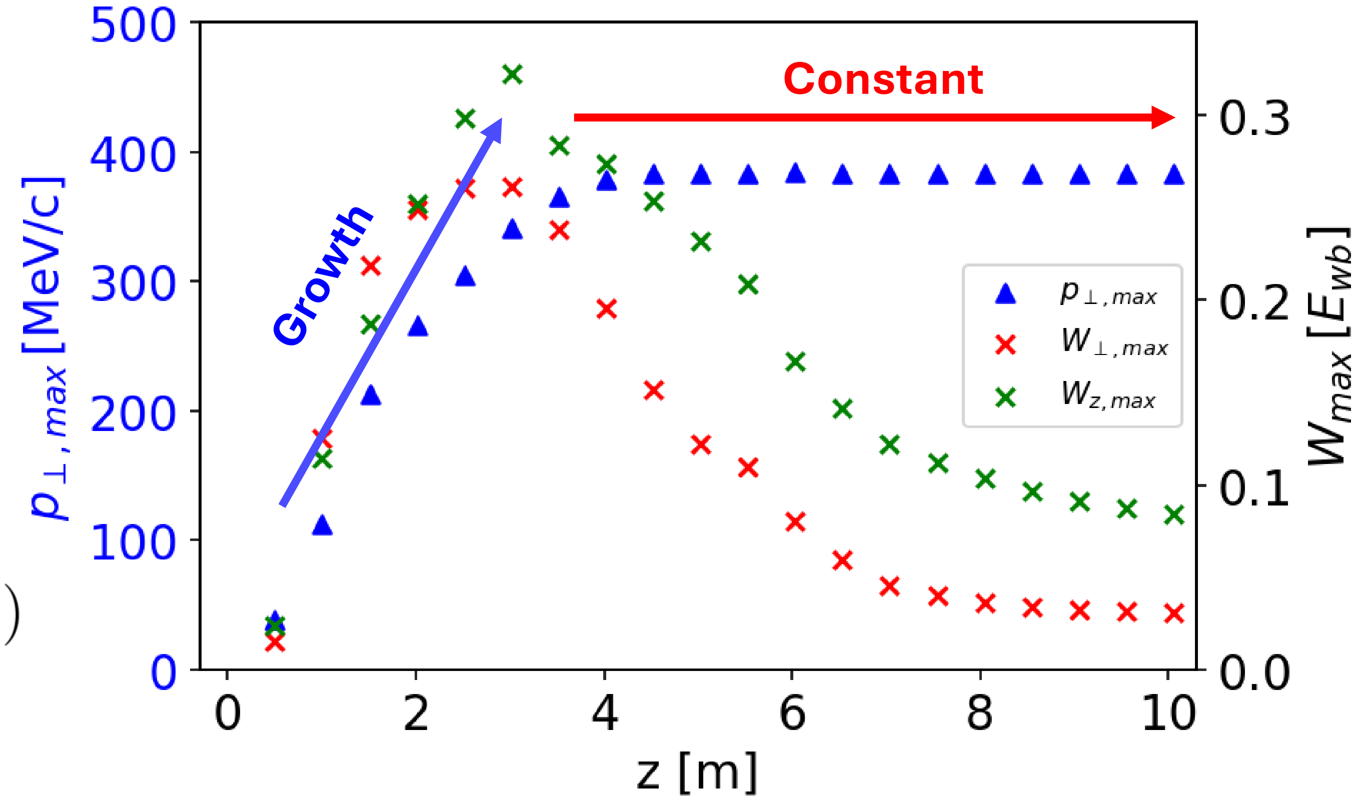
LCODE simulations

Because **SM is a transverse process** :

- Formation of **microbunch train** implies formation of **halo of defocused particles**

- **The transverse momentum** that defocused particles acquire is related to the **field amplitude** they experience:

$$p_{\perp} = \frac{q}{c}\int_0^L W_{\perp}(z,\xi,r)dz + p_{\perp 0}(z,\xi,r_0)$$



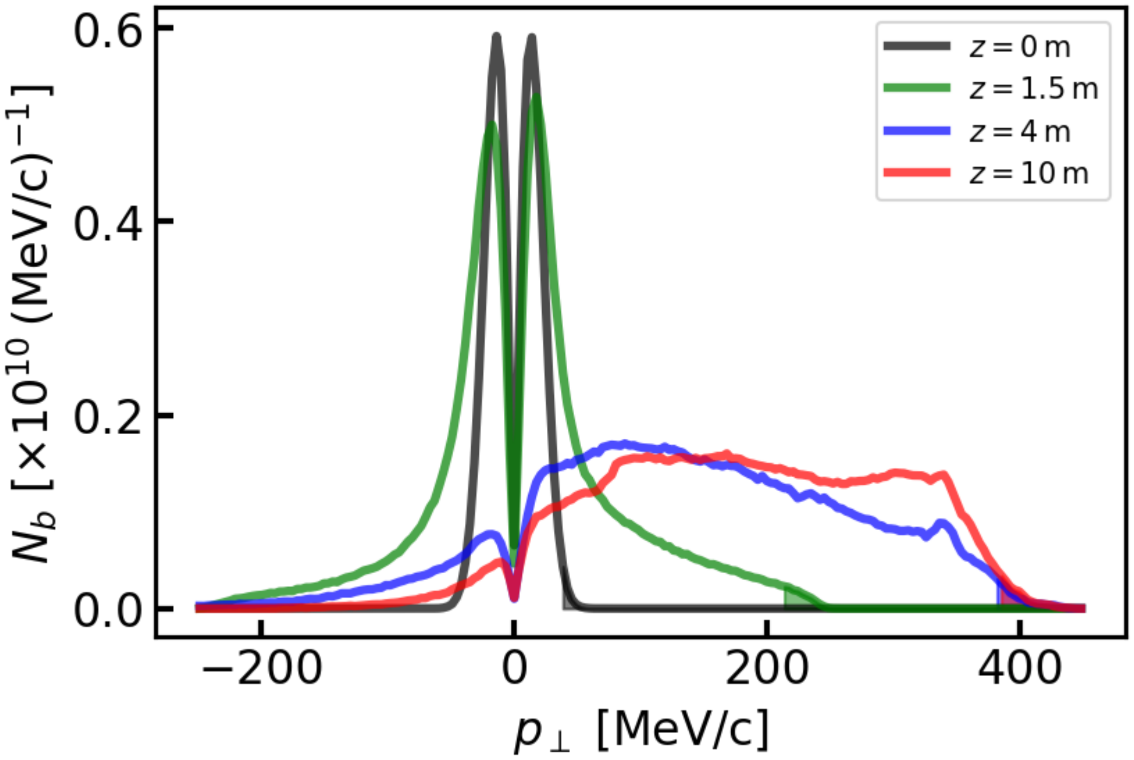
The **transverse momentum of the most defocused protons** first **increases** along the plasma and **becomes constant** approximately where **SM saturates**

Transverse momentum distribution

LCODE simulations

During growth of SM (black, green, blue curves):
- **Momentum** of most defocused particles (shaded area) **increases with z**

At and after saturation of SM (blue, red curves):
- Momentum of **most defocused** particles is **unchanged**
- More particles are **defocused but with smaller transverse momentum**



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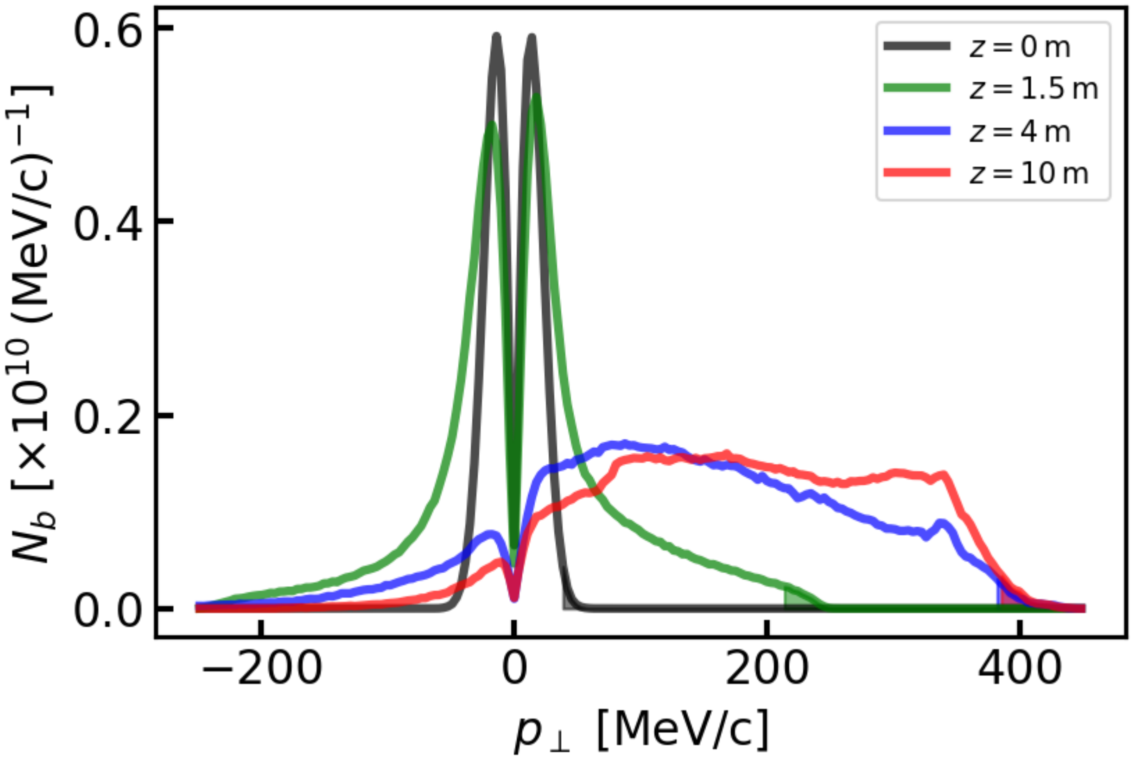


Around z=Lsat, the most defocused particles exit the wakefields transversely
No particles reach a larger momentum beyond that point

Transverse momentum evolution of particles

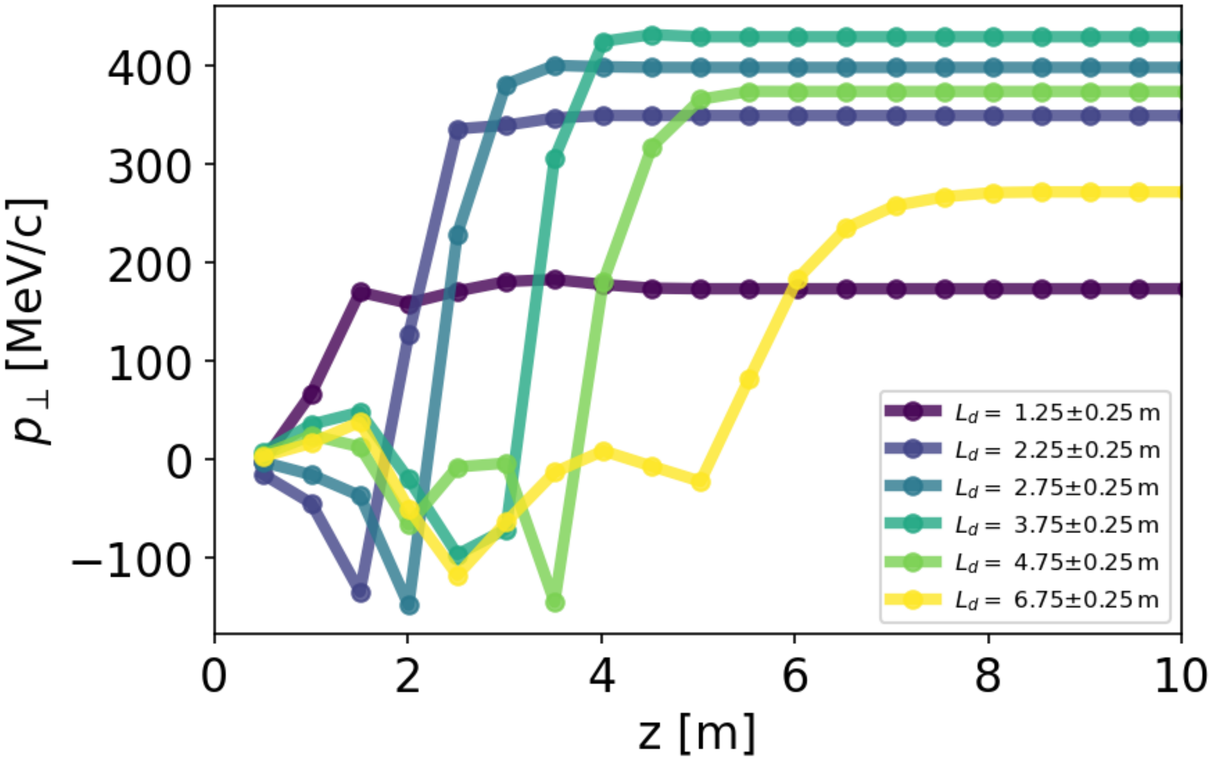
LCODE simulations

We track particles that exit wakefields transversely at different locations along z

During growth:
- Some particles exit the wakefields
- They do so with a smaller momenta than the most defocused particles at the plasma exit

At saturation:
- There are particles that leave the wakefields with a **very large transverse momentum**

After saturation:
- Particles leave the wakefields but with a **smaller** transverse momentum



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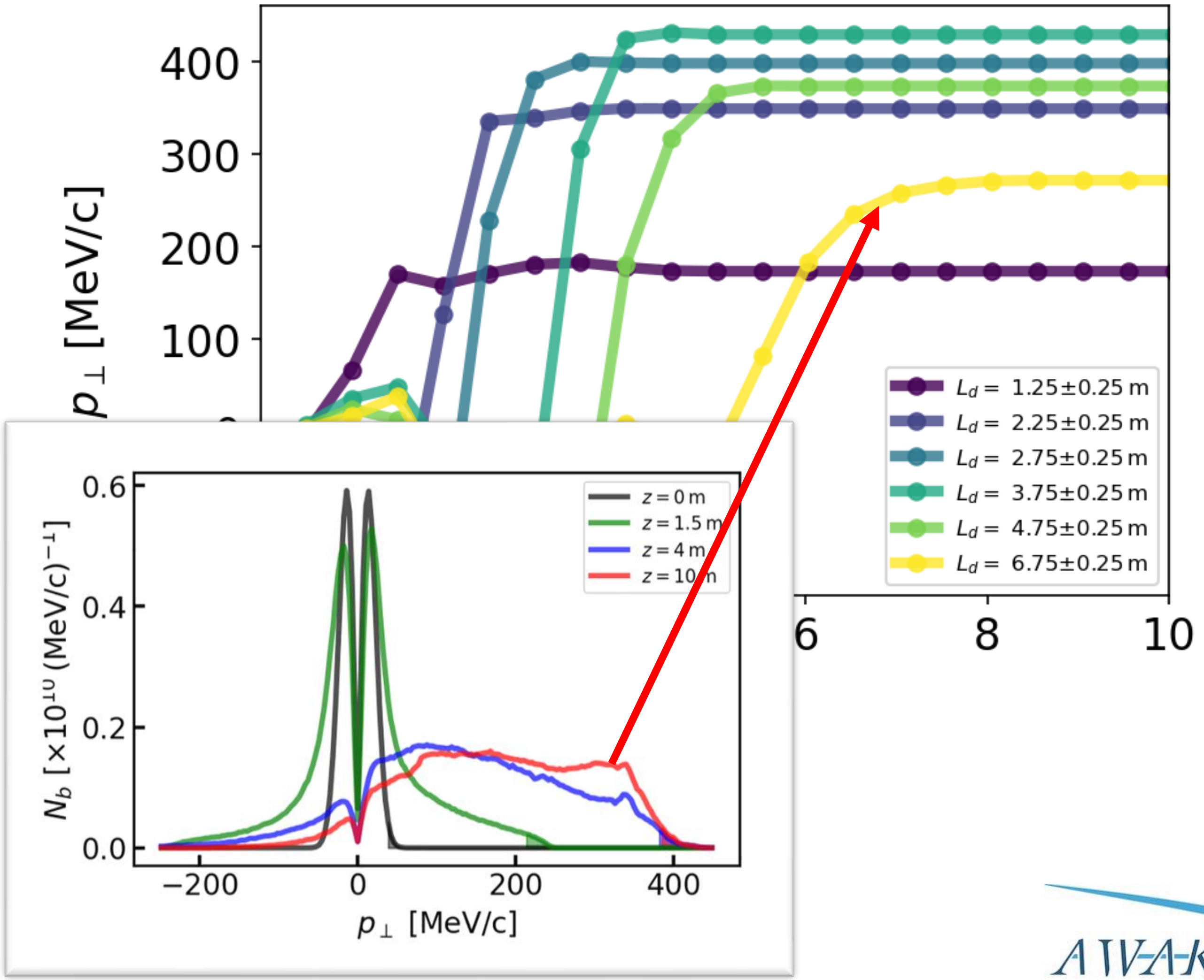


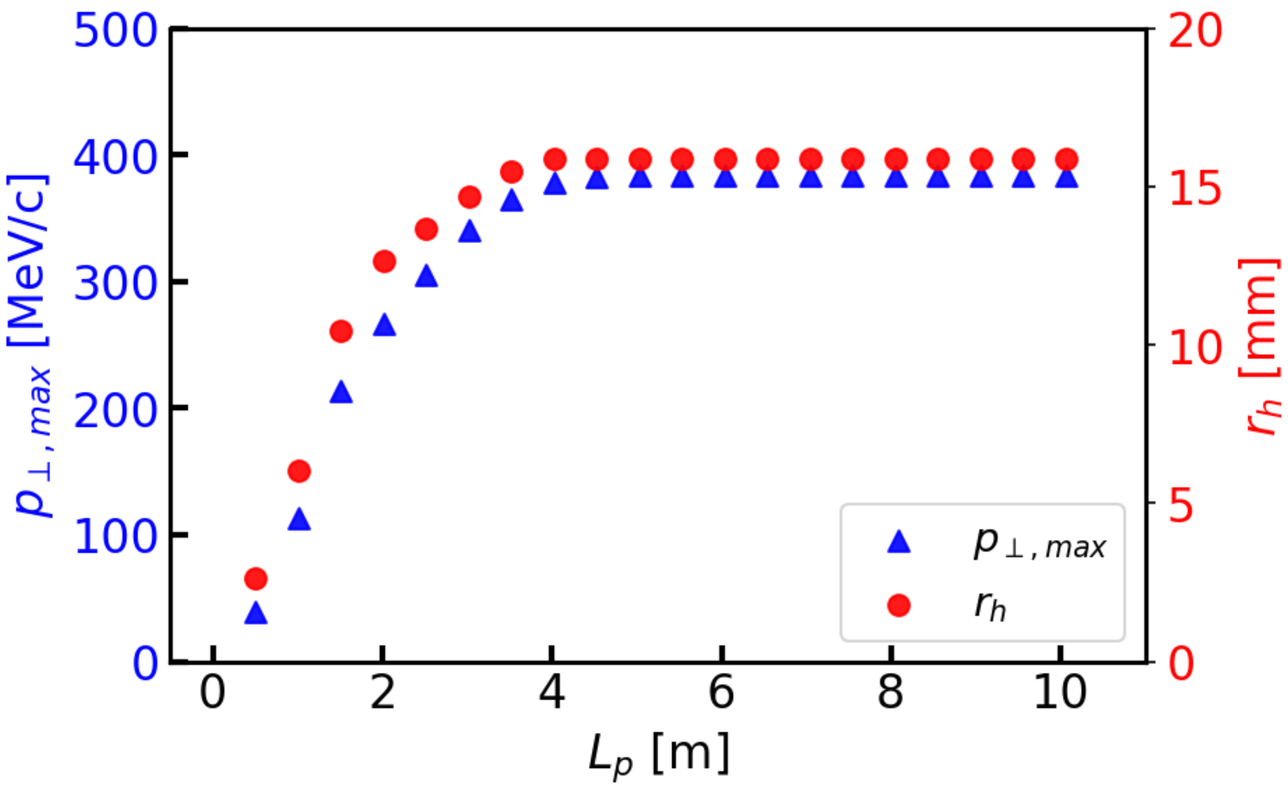
Transverse momentum vs z vs halo size

LCODE simulations

We showed that **measuring the location at which $p_{\perp,max}$ saturates** is approximately the **saturation length of SM**

In the experiment $p_{\perp,max}$ **vs z** cannot be measured directly:

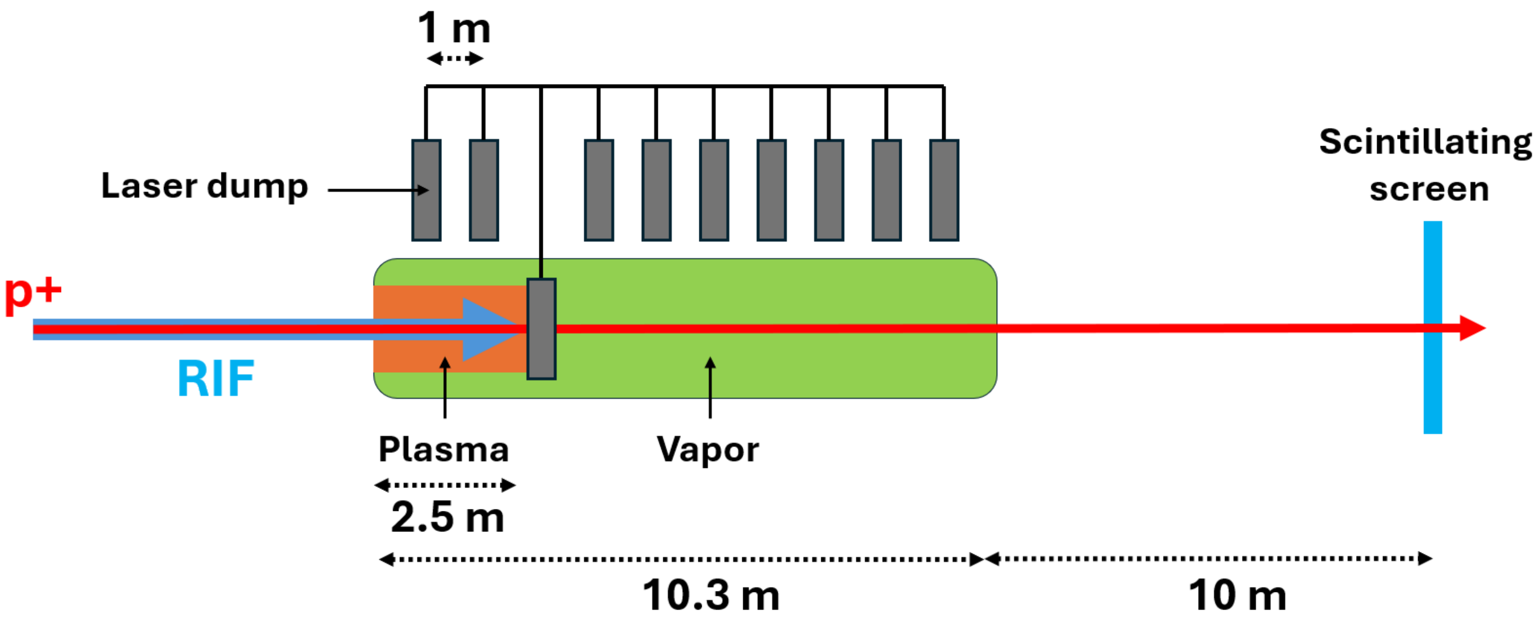
- We can instead measure **halo radius on a screen located 20m downstream of the plasma entrance** for different **plasma length**



We can measure the **saturation length of SM** by measuring the **plasma length** for which **the radius of the halo saturates**

Experimental setup

- **p+ and RIF** copropagate
- **RIF ionizes the vapor** such that protons are in plasma
- **RIF** can be **stopped** at different locations along the plasma by inserting **laser dumps**, thus **changing the plasma length**
- **Time-integrated transverse profile** of the bunch is observed **20m downstream of the plasma entrance**



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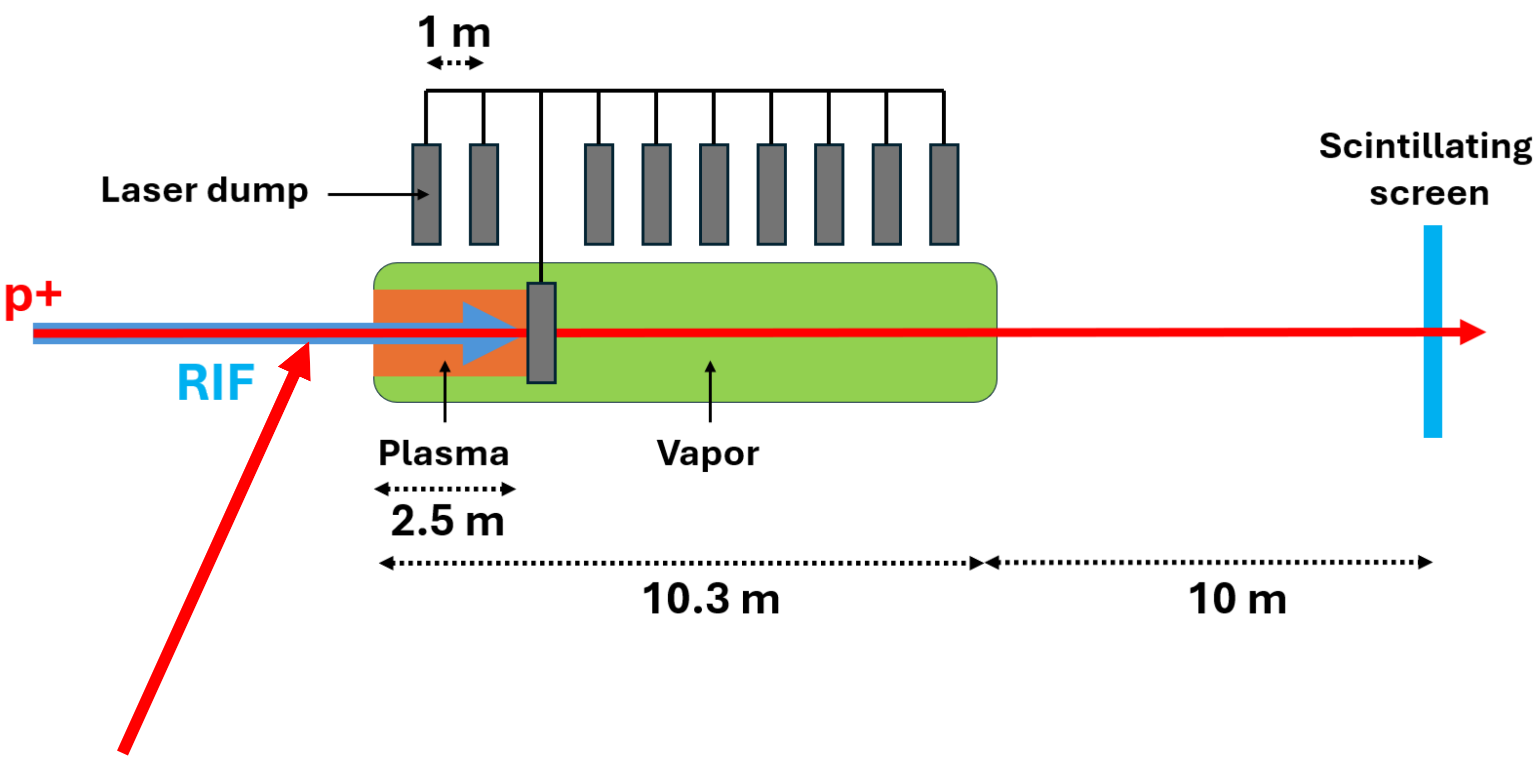

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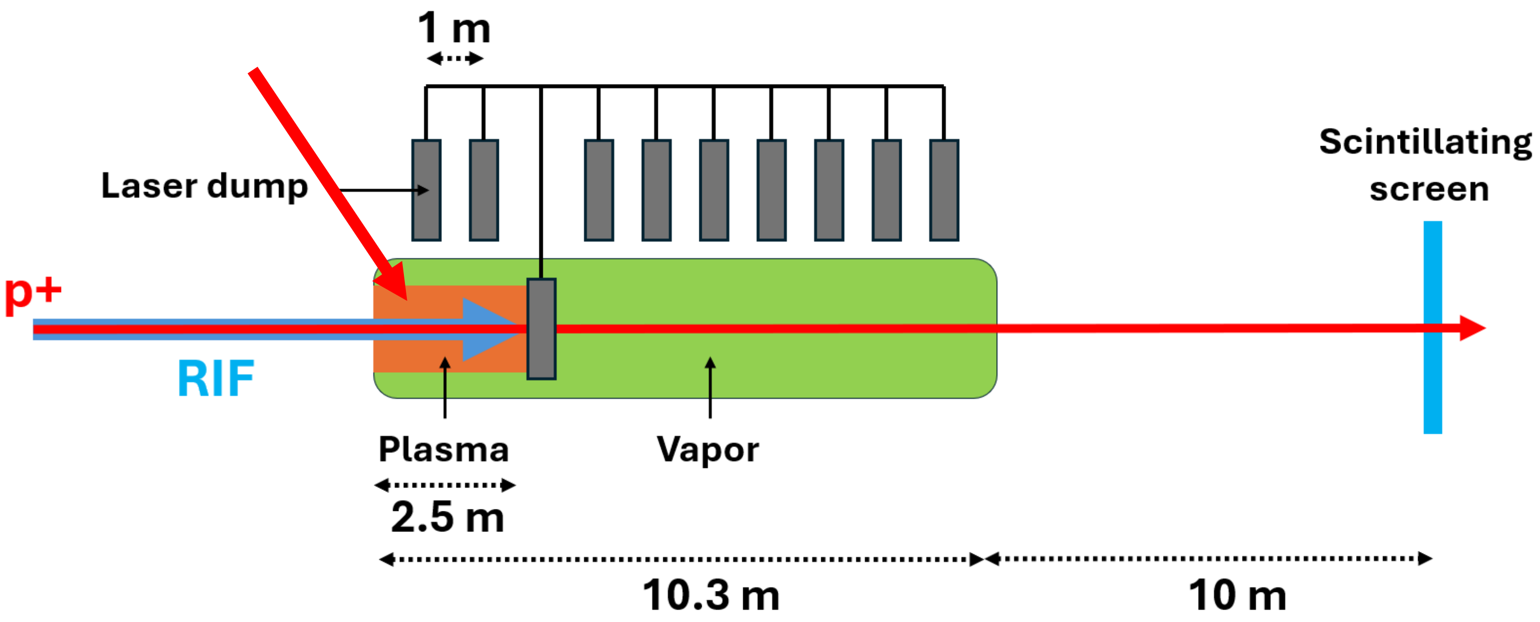

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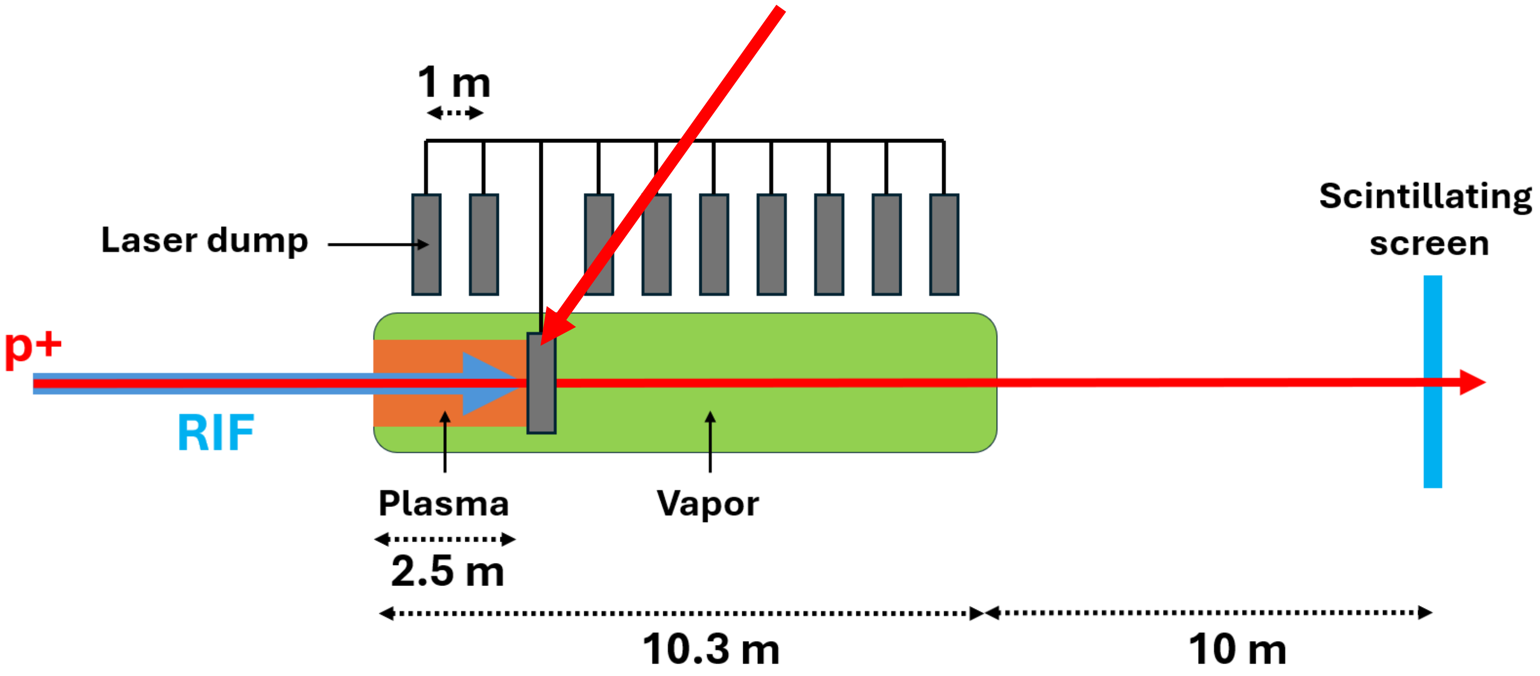

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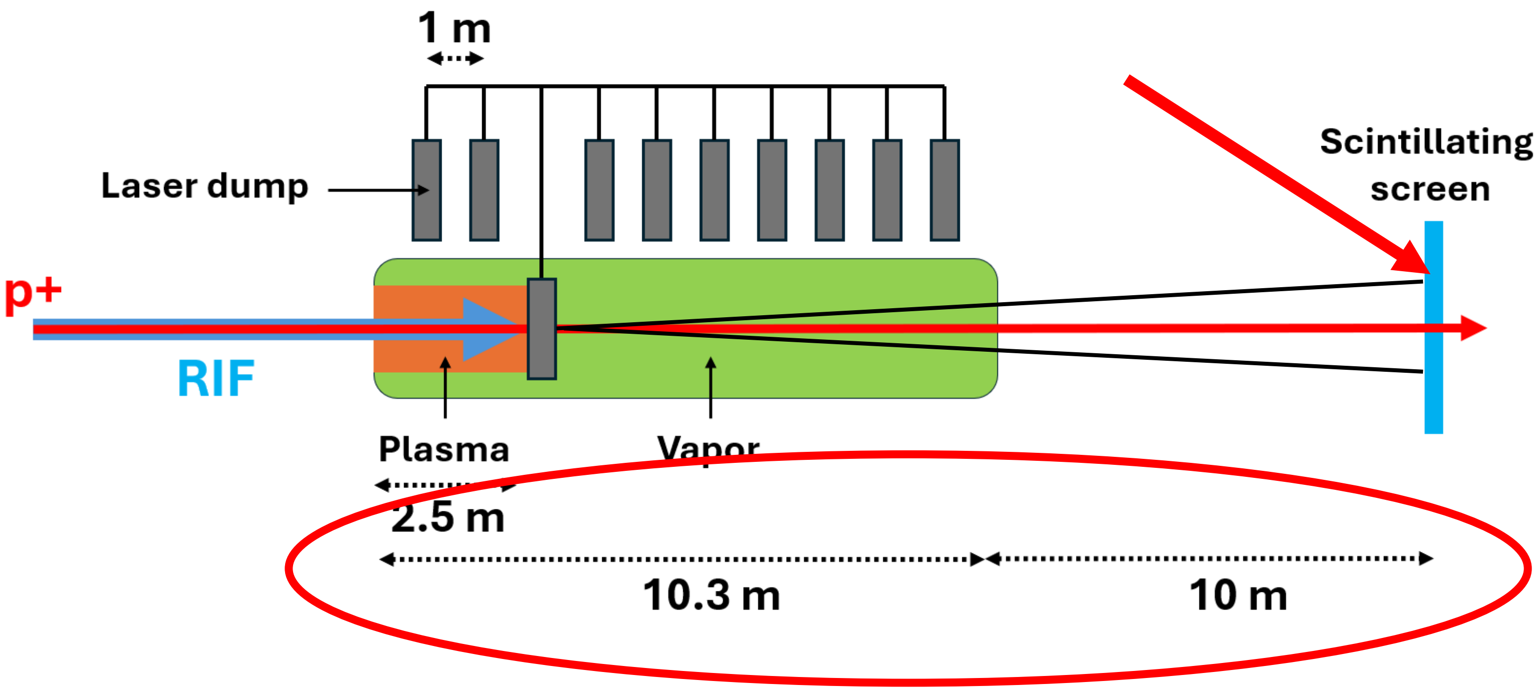
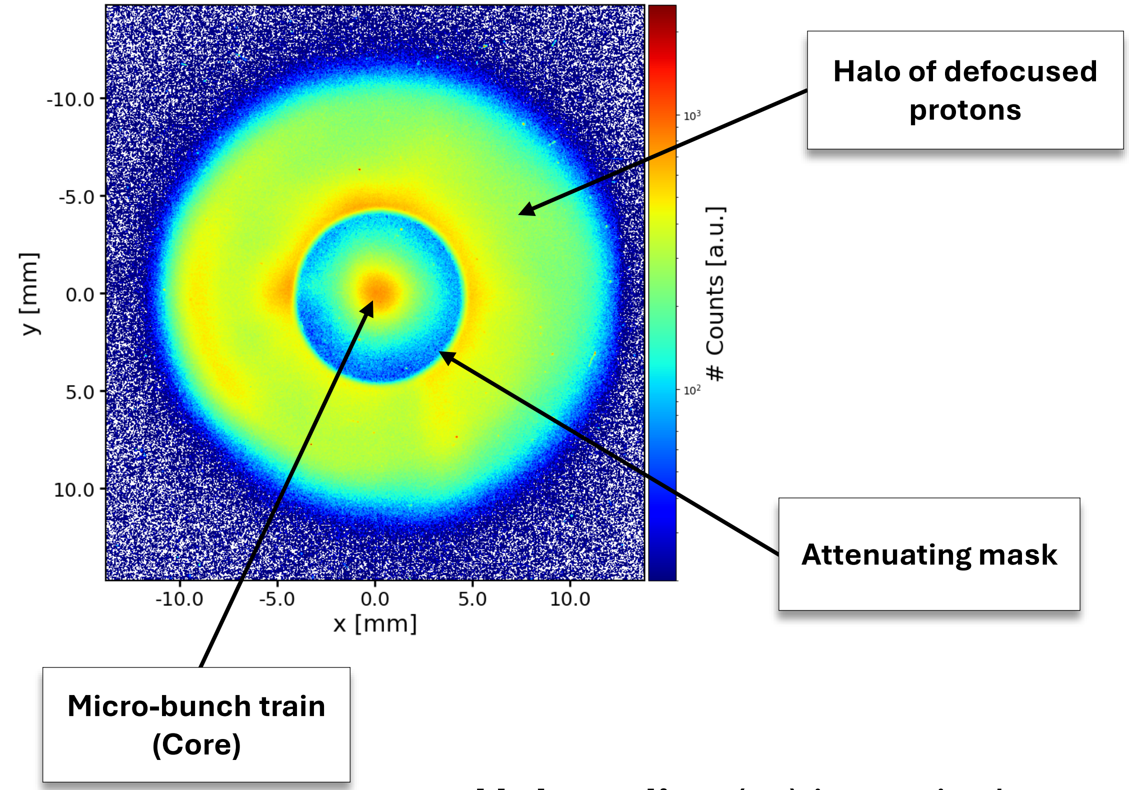
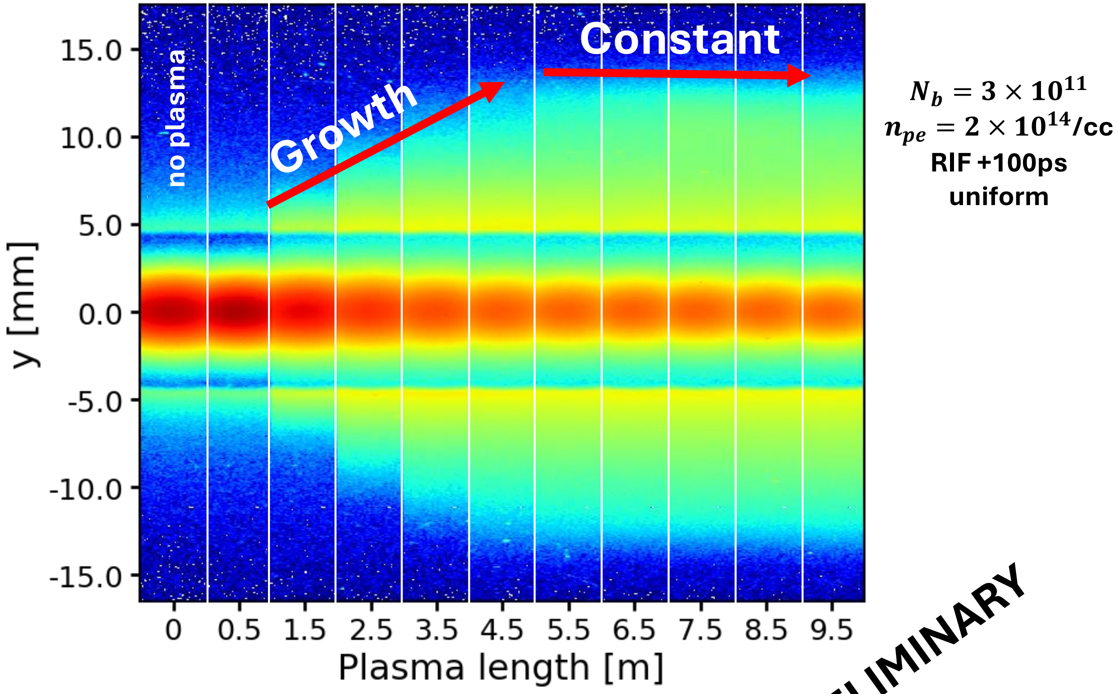


Experimental observations

After 10m of propagation in plasma and 10m of ballistic propagation to the screen



Vertical slice of halo for different plasma lengths



PRELIMINARY

Halo radius (r_h) is equivalent to $\boldsymbol{p_{\perp,max}}$ of the bunch at the **plasma exit**

- Both first increase with plasma length
- **Saturate** where **SM saturates**

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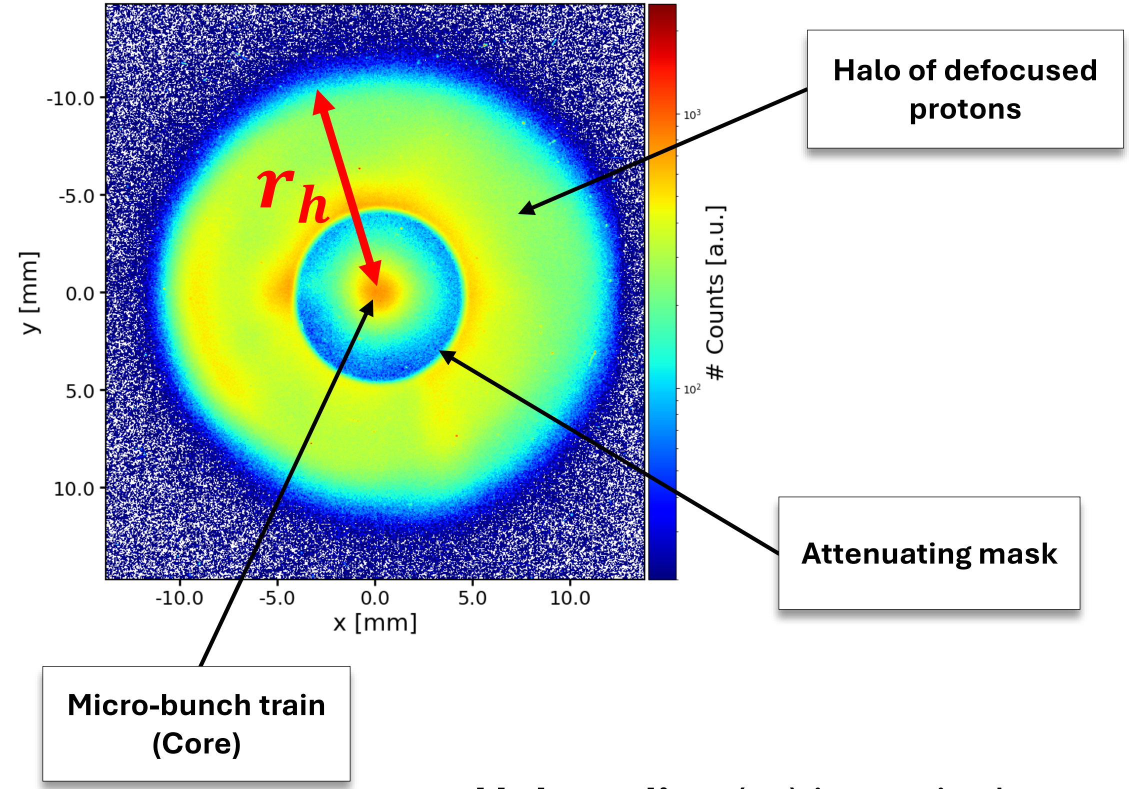

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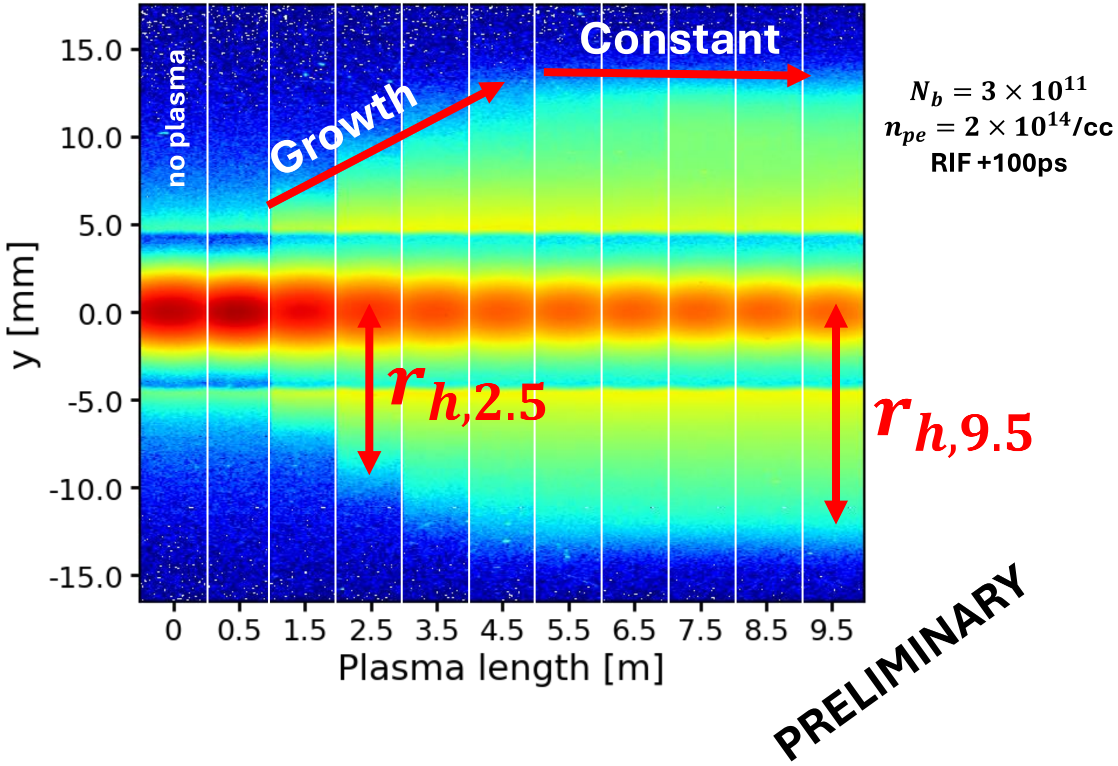

Halo radius (r_h) is equivalent to $p_{\perp,max}$ of the bunch at the **plasma exit**

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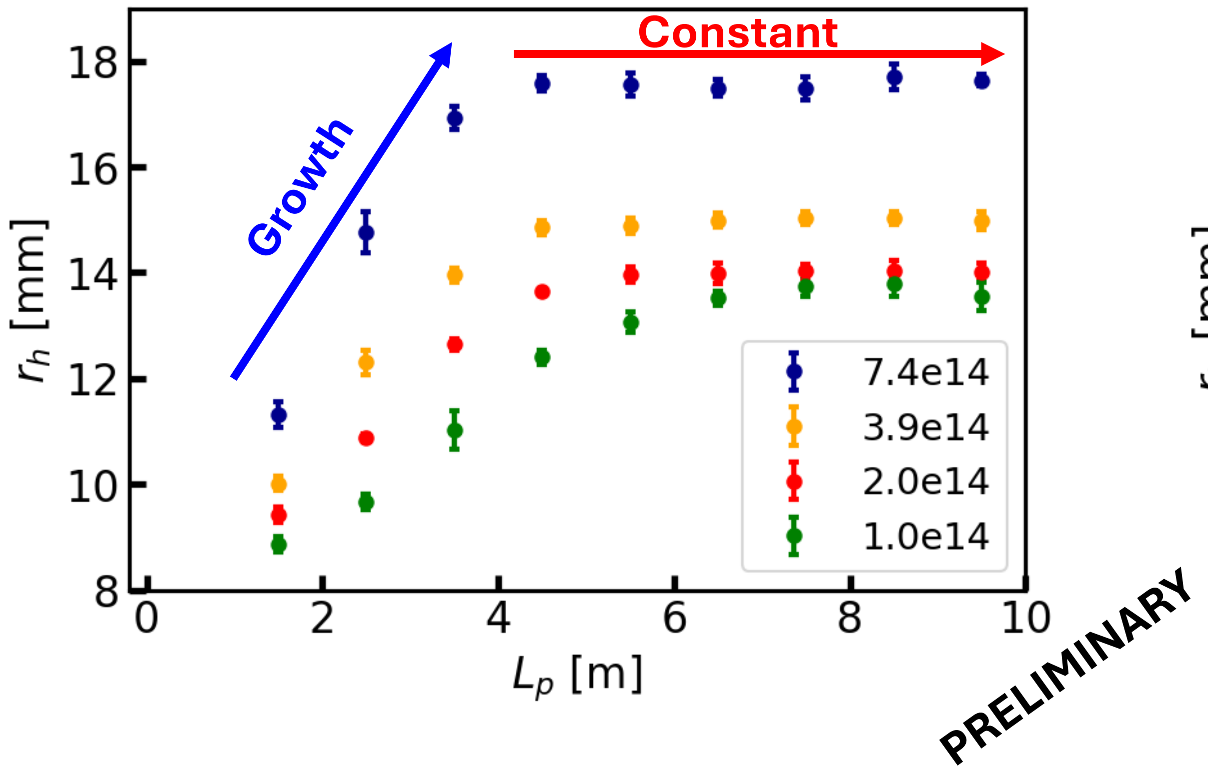
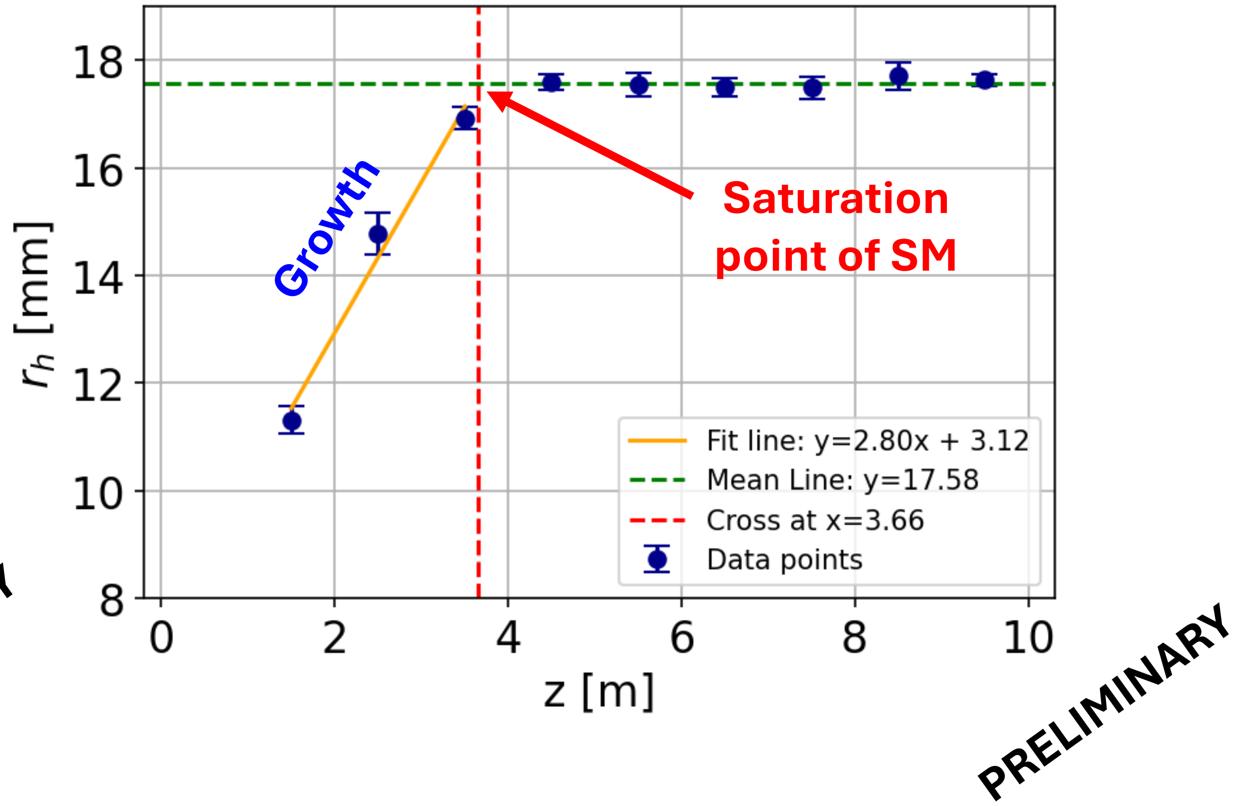
AWAKE

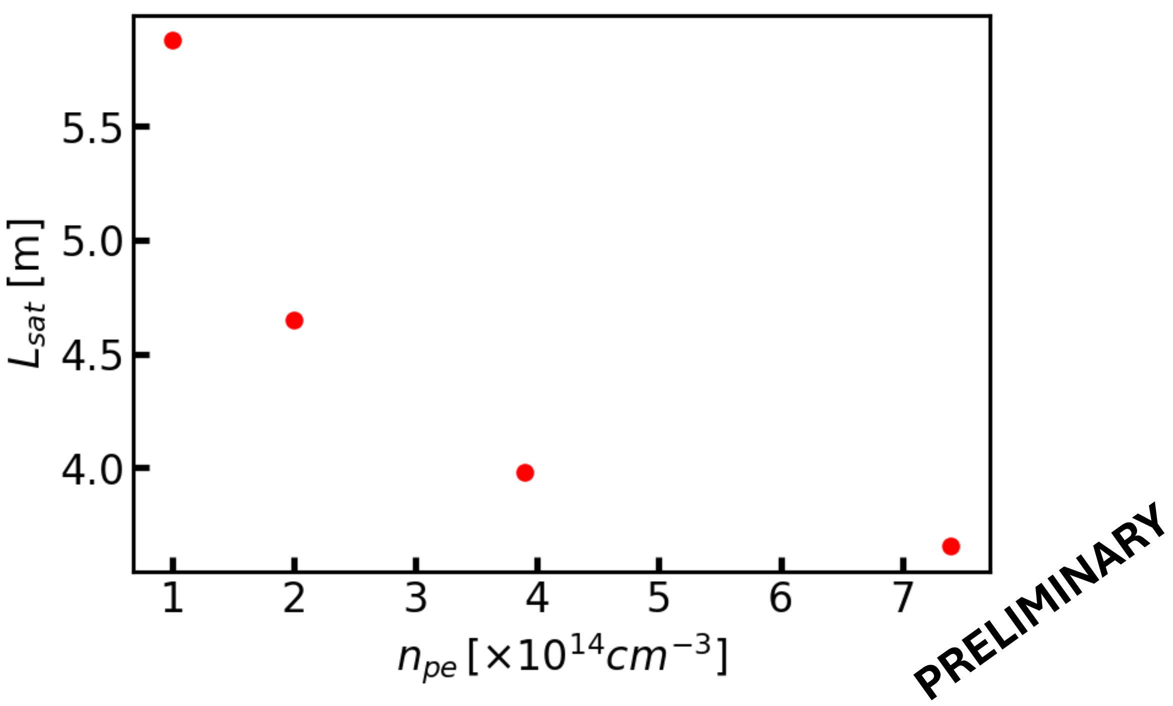
Experimental measurement of L_{sat}

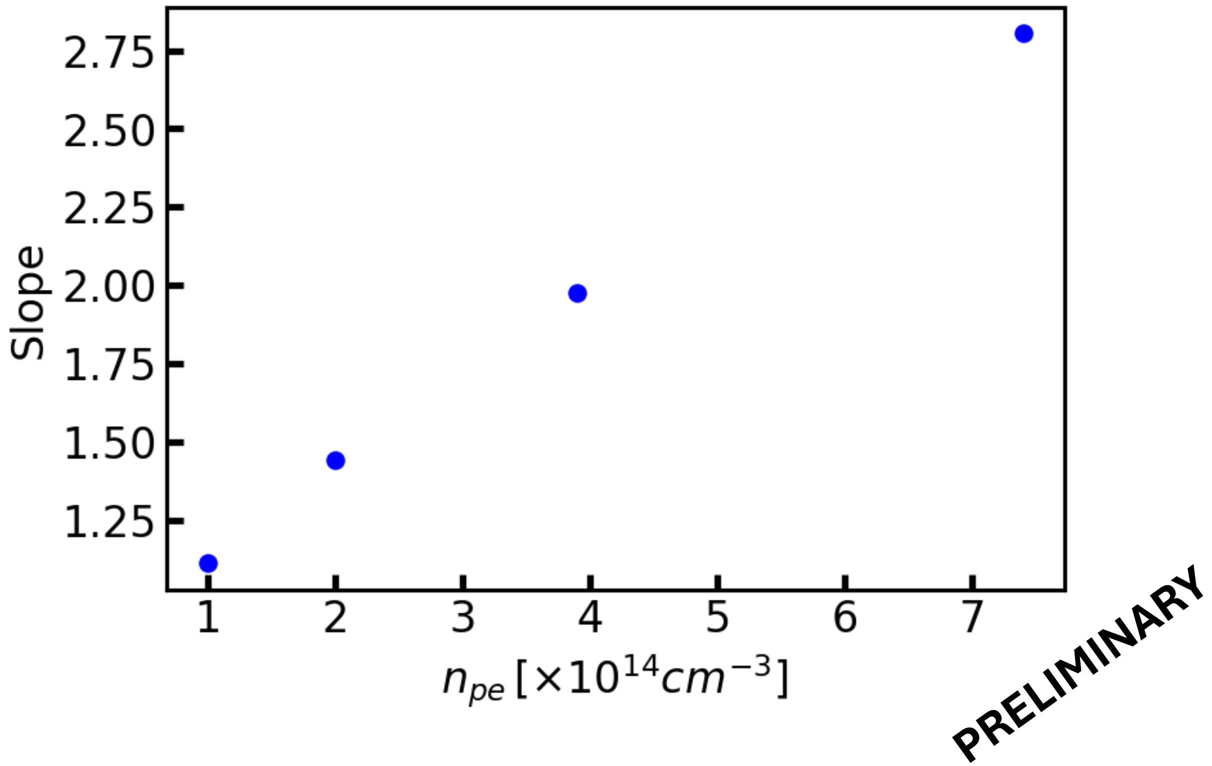




Repeat this measurement for **different plasma densities**
We extract both the **saturation length** and the **"slope of the growth"**

Saturation length for different plasma densities





The **saturation length of SM decreases** with plasma density

It varies between **6m and 3.5m** for $n_{pe} = 1 - 7.4 \times 10^{14}$/cc

The **slope of the growth increases** lineary with plasma density

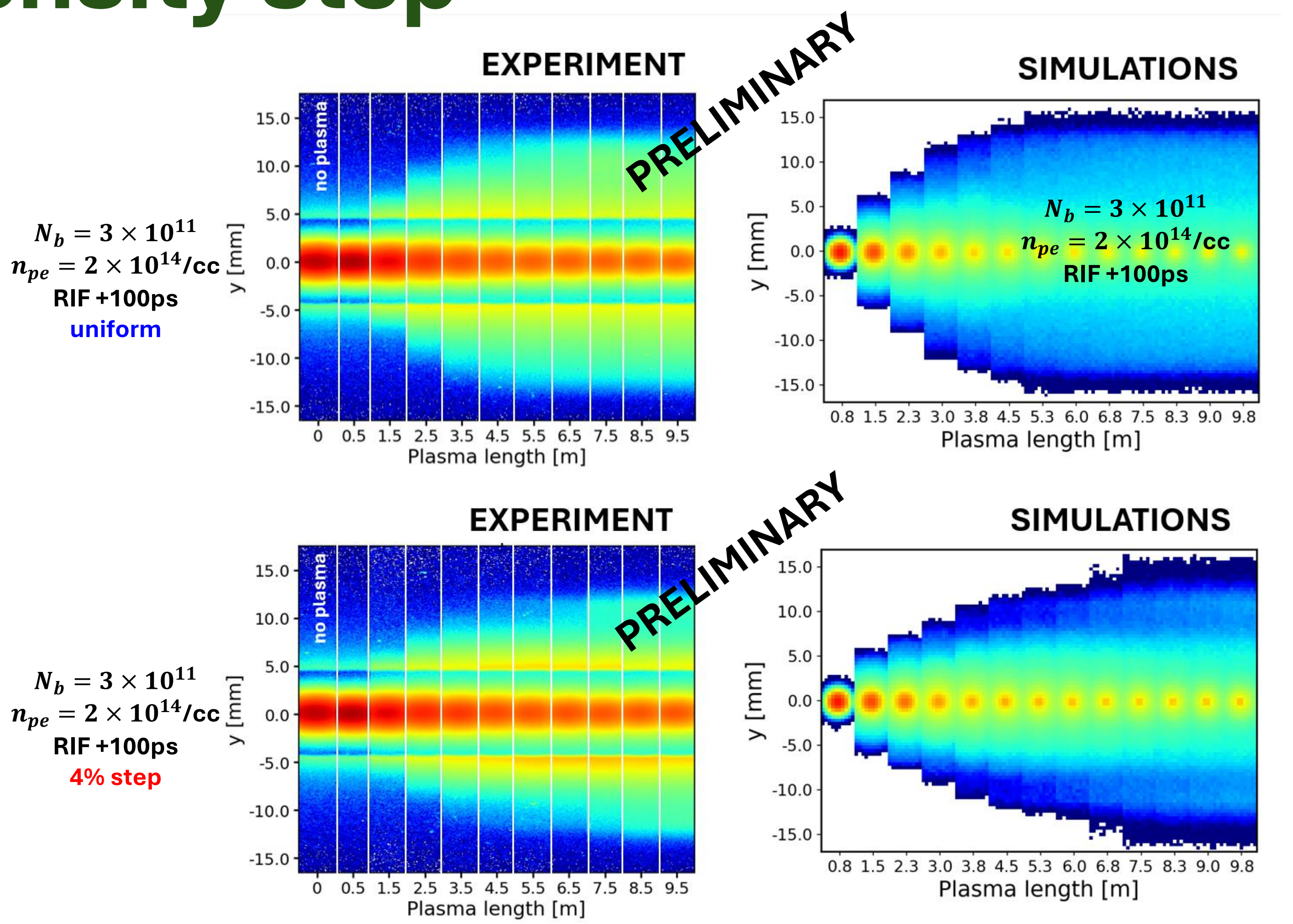
Evolution of the halo with and without plasma density step

The **evolution** of SM changes with a **plasma density step**

The saturation occurs later along the plasma

Experimental results show similar evolution as seen in the simulation

➔ Additional evidence that the plasma density step does affect the p+ bunch as intended



Summary - Conclusions

The saturation length of SM is an important quantity to measure, both for physics and for run 2c

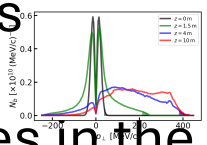
- **Using LCODE simulations :**
  - We show that the **plasma length** for which the **radius of the halo saturates** is approximately where the **saturation of SM occurs**

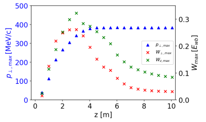
- **In the experiment :**
  - **Halo radius first increases** along the plasma and **then saturates** – similarly to what was seen in simulation
  - We therefore **measured the saturation length** of SM for multiple plasma densities
  - We show that the **saturation length of SM decreases with $\boldsymbol{n_{pe}}$** and varies from **6m to 3.5m** for $\boldsymbol{n_{pe} = 1 - 7.4 \times 10^{14}}$**/cc**

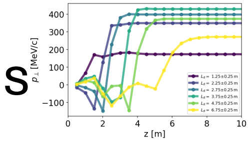
  - We show that the **effect of the density step** is visible on the halo when varying the plasma length – in particular we observe that the growth is delayed

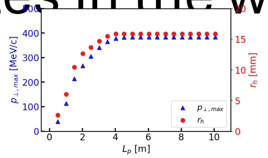
Program

- Principle of the measurement
- Simulations
  - p_perp vs wakefields
  - P_perp distribution
  - Trajectory of particles in the wakefields
  - P_perp vs halo size

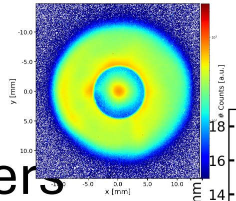


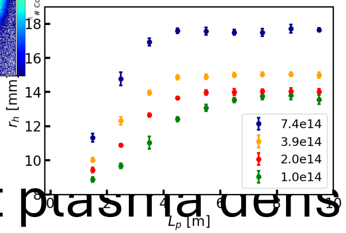






- Experimental results
  - Halo
  - Waterfall plot, plungers
  - Size vs plasma length
  - Saturation point for different plasma densities
  - Growth rate ?





- Conclusion and summary