Experimental measurement of the amplitude reproducibility of SM

Arthur CLAIREMBAUD
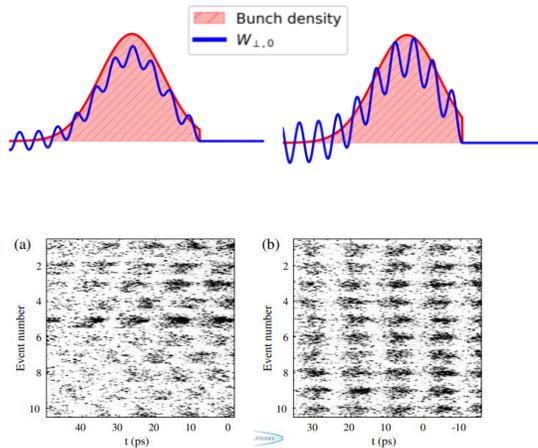
Seeding of SM

Transition between Instability and Seeded Self-Modulation of a Relativistic Particle Bunch in Plasma

F. Batsch, P. Muggli, R. Agnello, C. C. Ahdida, M. C. Amoedo Goncalves, Y. Andrebe, O. Apsimon, R. Apsimon, A.-M. Bachmann, M. A. Baistrukov, P. Blanchard, F. Braunmüller, P. N. Burrows, B. Buttenschön, A. Caldwell, J. Chappell, E. Chevallay, M. Chung, D. A. Cooke, H. Damerau, C. Davut, G. Demeter, H. L. Deubner, S. Doebert, J. Farmer, A. Fasoli, V. N. Fedosseev, R. Fiorito, R. A. Fonseca, F. Friebel, I. Furno, L. Garolfi, S. Gessner, I. Gorgisyan, A. A. Gorn, E. Granados, M. Granetzny, T. Graubner, O. Grulke, E. Gschwendtner, V. Hafych, A. Helm, J. R. Henderson, M. Hüther, I. Yu. Kargapolov, S.-Y. Kim, F. Kraus, M. Krupa, T. Lefevre, L. Liang, S. Liu, N. Lopes, K. V. Lotov, M. Martyanov, S. Mazzoni, D. Medina Godoy, V. A. Minakov, J. T. Moody, K. Moon, P. I. Morales Guzmán, M. Moreira, T. Nechaeva, E. Nowak, C. Pakuza, H. Panuganti, A. Pardons, A. Perera, J. Pucek, J. Pusztai, A. Pukhov, R. L. Ramjiawan, S. Rey, K. Rieger, O. Schmitz, E. Senes, L. O. Silva, R. Speroni, R. I. Spitsyn, C. Stollberg, A. Sublet, A. Topaloudis, N. Torrado, P. V. Tuev, M. Turner, P. Velotti, L. Verra, V. A. Verzilov, J. Vieira, H. Vincke, C. P. Welsch, M. Wendt, M. Wing, P. Wiwattananon, J. Wolfenden, B. Woolley, G. Xia, M. Zepp, and G. Zevi Della Porta

(AWAKE Collaboration)

Seeding demonstrated in Fabian's PRL
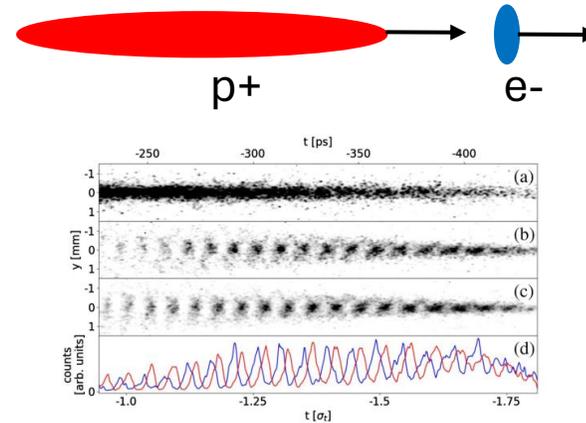- RIF: beam-plasma density onset drives initial wakefields

Editors' Suggestion   Featured in Physics

Controlled Growth of the Self-Modulation of a Relativistic Proton Bunch in Plasma

L. Verra, G. Zevi Della Porta, J. Pucek, T. Nechaeva, S. Wyler, M. Bergamaschi, E. Senes, E. Guran, J. T. Moody, M. Á. Kedves, E. Gschwendtner, and P. Muggli

(AWAKE Collaboration)

p+   e-

Seeding also demonstrated in Livio's PRL
- Preceeding electron bunch provides initial wakefields

- Self-modulation can develop from noise or features in the longitudinal bunch distribution
- SMI: We don't control the initial conditions from which the instability develops

- Self-modulation can also be seeded
- SSM: We define the initial conditions from which the instability grows

Seeding makes the timing of the microbunches – and thus the phase of the wakefields reproducible
➔ Key for deterministic injection
➔ Amplitude reproducibility of SM process is yet to be shown

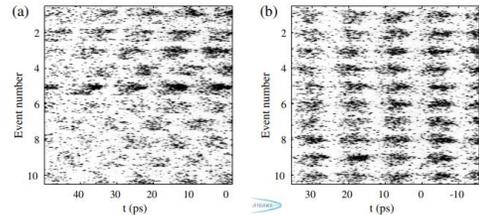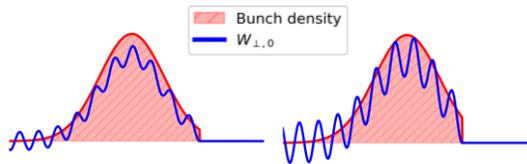# Seeding of SM

Transition between Instability and Seeded Self-Modulation of a Relativistic Particle Bunch in Plasma

F. Batsch,[1] P. Muggli,[1] R. Agnello,[2] C. C. Ahdida,[3] M. C. Amoedo Goncalves,[3] Y. Andrebe,[2] O. Apsimon,[4,5] R. Apsimon,[4,6] A.-M. Bachmann,[1] M. A. Baistrukov,[7,8] P. Blanchard,[2] F. Braunmüller,[1] P. N. Burrows,[9] B. Buttenschön,[10] A. Caldwell,[1] J. Chappell,[11] E. Chevallay,[3] M. Chung,[12] D. A. Cooke,[11] H. Damerau,[3] C. Davut,[4,13] G. Demeter,[14] H. L. Deubner,[15] S. Doebert,[3] J. Farmer,[1,3] A. Fasoli,[2] V. N. Fedosseev,[3] R. Fiorito,[4,5] R. A. Fonseca,[16,17] F. Friebel,[3] I. Furno,[2] L. Garolfi,[18] S. Gessner,[19] I. Gorgisyan,[3] A. A. Gorn,[7,8] E. Granados,[3] M. Granetzny,[20] T. Graubner,[15] O. Grulke,[10,21] E. Gschwendtner,[3] V. Hafych,[1] A. Helm,[17] J. R. Henderson,[4,22] M. Hüther,[1] I. Yu. Kargapolov,[7,8] S.-Y. Kim,[12] F. Kraus,[15] M. Krupa,[3] T. Lefevre,[3] L. Liang,[4,13] S. Liu,[18] N. Lopes,[17] K. V. Lotov,[7,8] M. Martyanov,[1] S. Mazzoni,[3] D. Medina Godoy,[3] V. A. Minakov,[7,8] J. T. Moody,[1] K. Moon,[12] P. I. Morales Guzmán,[1] M. Moreira,[3,17] T. Nechaeva,[1] E. Nowak,[3] C. Pakuza,[9] H. Panuganti,[3] A. Pardons,[3] A. Perera,[4,5] J. Pucek,[1] J. Pukhov,[23] R. L. Ramjiawan,[3,9] S. Rey,[3] K. Rieger,[1] O. Schmitz,[20] E. Senes,[3,9] L. O. Silva,[17] R. Speroni,[3] R. I. Spitsyn,[7,8] C. Stollberg,[2] A. Sublet,[3] A. Topaloudis,[3] N. Torrado,[17] P. V. Tuev,[7,8] M. Turner,[3] F. Velotti,[3] L. Verra,[1,3,25] V. A. Verzilov,[18] J. Vieira,[17] H. Vincke,[3] C. P. Welsch,[4,5] M. Wendt,[3] M. Wing,[11] P. Wiwattananon,[3] J. Wolfenden,[4,5] B. Woolley,[3] G. Xia,[4,13] M. Zepp,[20] and G. Zevi Della Porta[3]

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Seeding demonstrated in Fabian's PRL
- RIF: beam-plasma density onset drives initial wakefields

Editors' Suggestion   Featured in Physics

Controlled Growth of the Self-Modulation of a Relativistic Proton Bunch in Plasma

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Seeding also demonstrated in Livio's PRL
- Preceeding electron bunch provides initial wakefields

Does seeding also make the amplitude of the wakefields reproducible from shot-to-shot ?
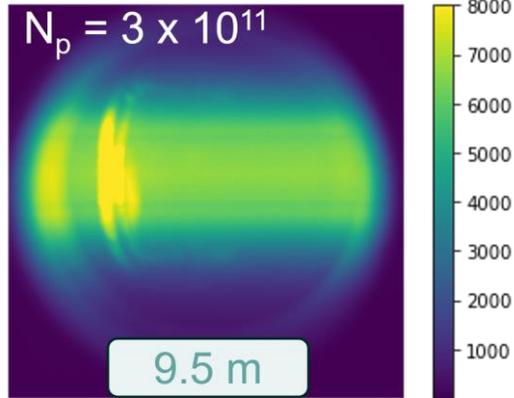
- Self-modulation can develop from noise or features in the longitudinal bunch distribution
- SM: We don't control the initial conditions from which the instability grows

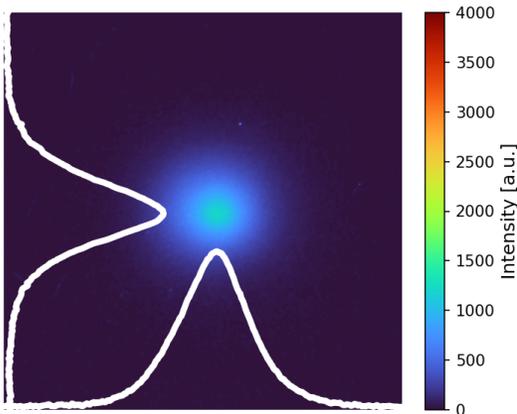- Modulation can also be seeded → we define the initial conditions from which the instability grows

Seeding makes the timing of the microbunches – and thus the phase of the wakefields reproducible
➔ Key for deterministic injection
➔ Amplitude reproducibility of SM process is yet to be shown

Wakefield amplitude diagnostics
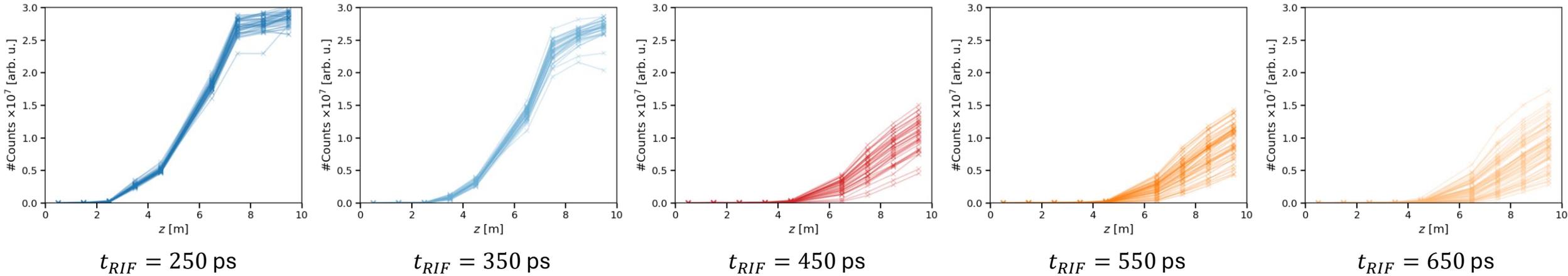
Plasma light

Transverse bunch profile

Indirect diagnostics !

- We have no direct measurement of the wakefield amplitude
- We can however look at indirect effect of the wakefields

- **Plasma light** emitted by wakefield dissipation
  - Expectation that light is prop. to W^2
  - Only local at low bunch population

- **Effect of transverse wakefields** on the bunch
  - Integrated over the prop. distance in plasma
  - No visible halo at low bunch population
  - Still, some effect on the transverse profile
  - No expected dependency with W

Plasma light results

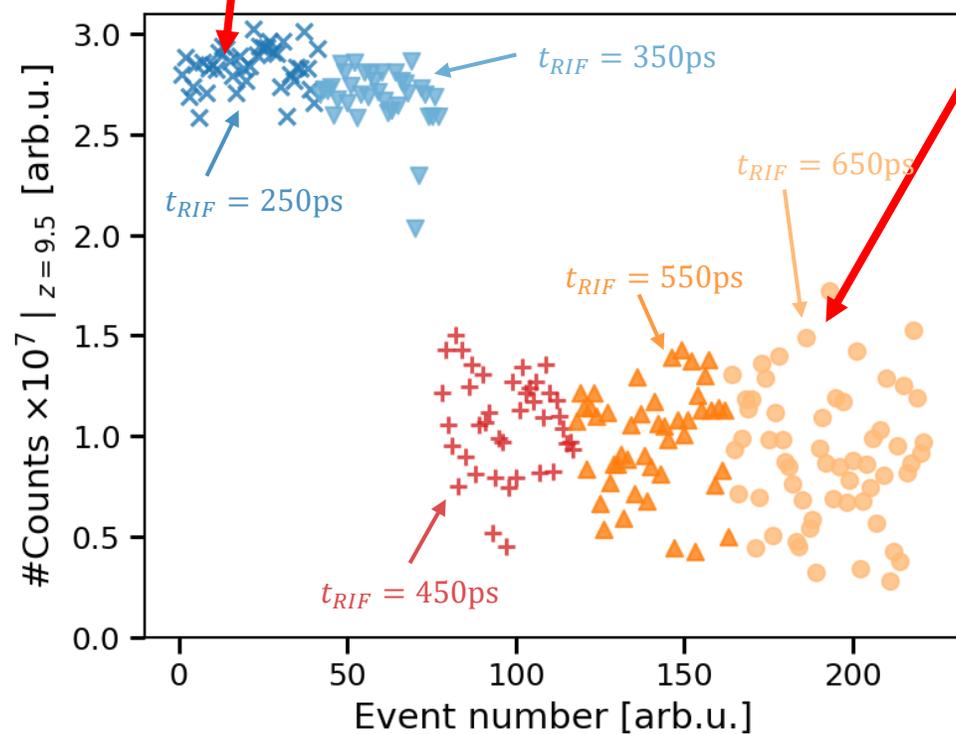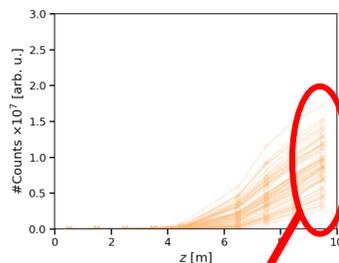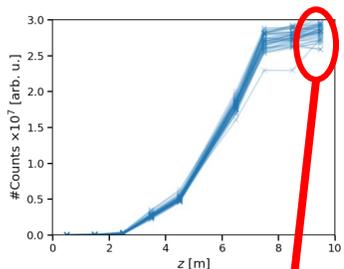$t_{RIF} = 250$ ps $t_{RIF} = 350$ ps $t_{RIF} = 450$ ps $t_{RIF} = 550$ ps $t_{RIF} = 650$ ps

- Plasma light emission along the plasma
- 5 different RIF positions ➜ Different initial field amplitudes
- ~ 50 events per data set
- Signal is local for these parameters ($N_b = 5 \times 10^{10}$)
- Signal grows along the plasma
  - Saturates for $t_{RIF} = 250, 350$ ps
  - Does not saturate for $t_{RIF} = 450, 550, 650$ ps
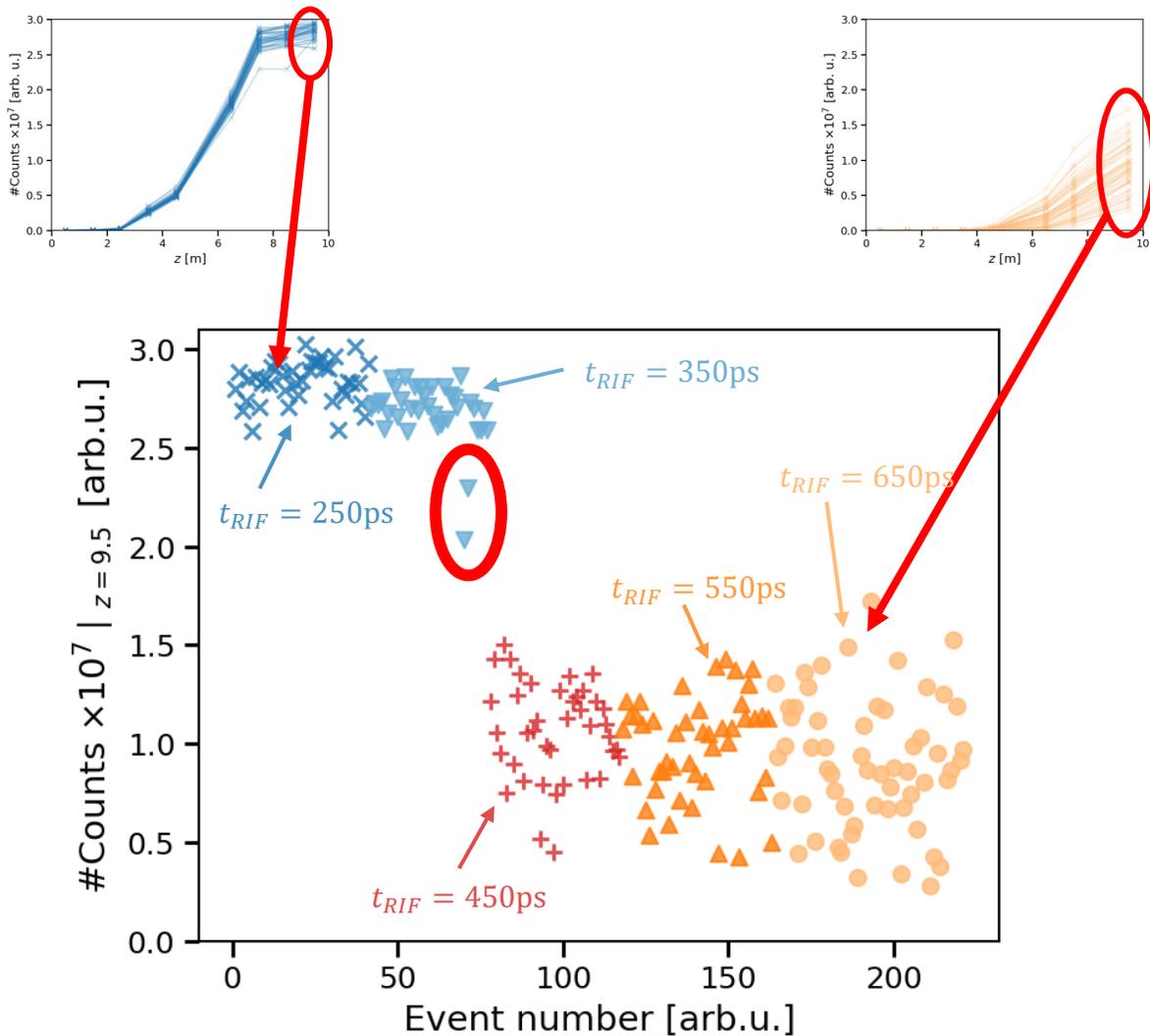- Signal below detection threshold for first cameras

- Variations much larger for $t_{rif} \geq 450$ ps
- Initial wakefields are no longer (always?) set by the RIF
- Initial wakefields come from non-reproducible noise, or features in the bunch ➜ SMI
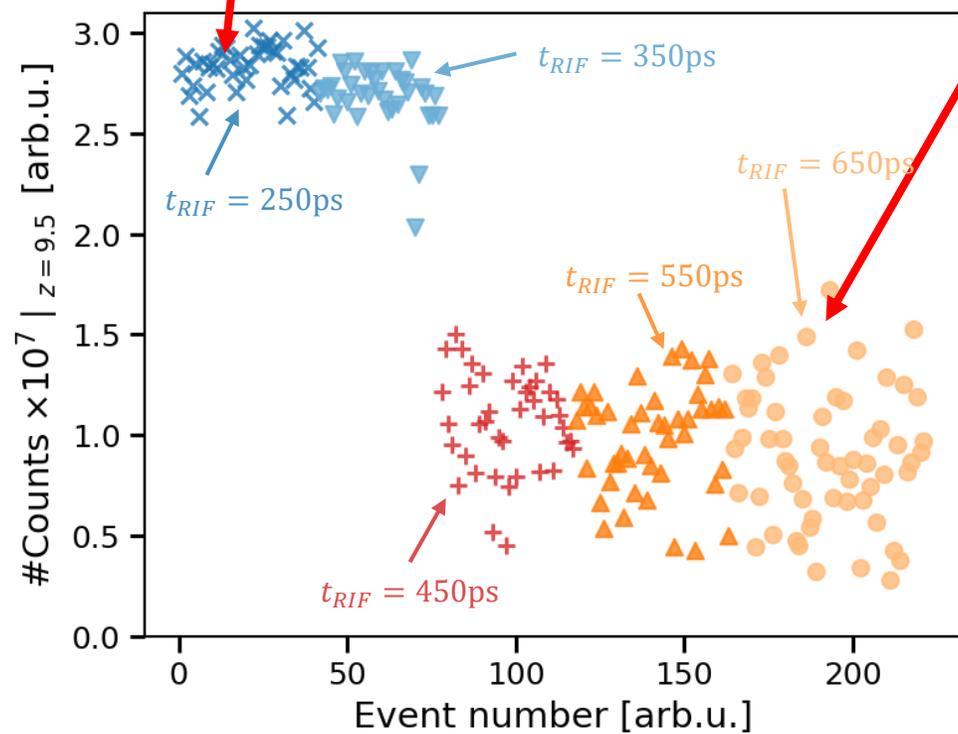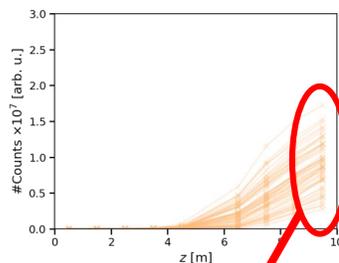
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SSM

SMI

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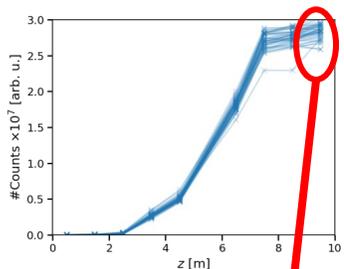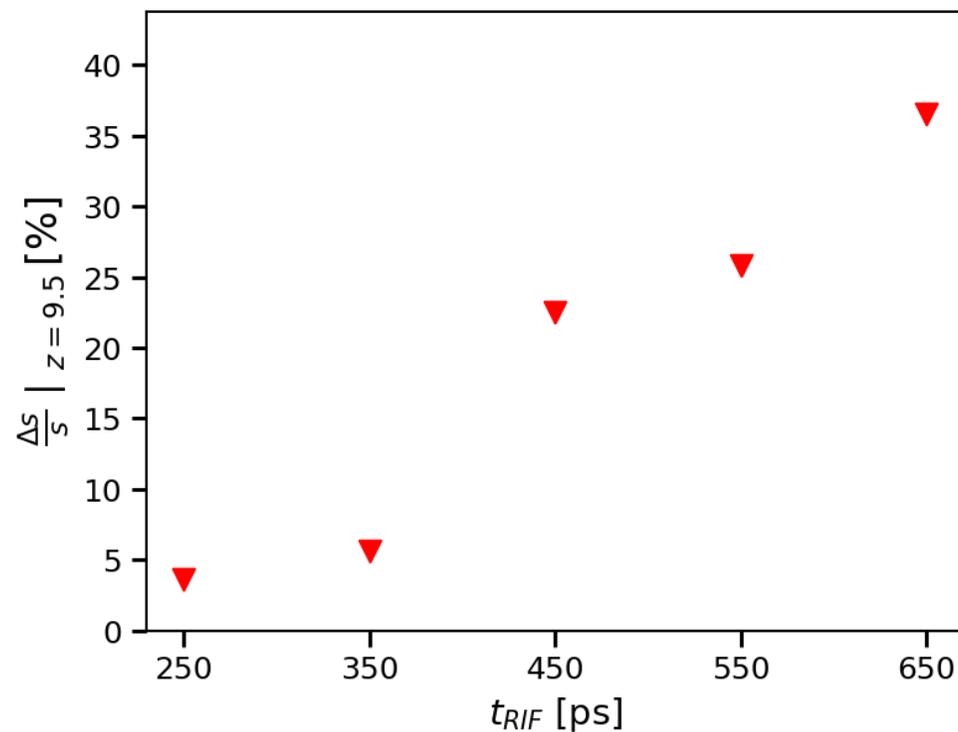
Plasma light, SSM and SMI

- We pick one camera (z=9.5m)
- Each event is displayed, for each RIF

- Clear difference in reproducibility
- SSM events are always above SMI
- Consistent with the fact that ΔN_b is small, and $W_{\perp,0,SSM} > W_{\perp,0,SMI}$

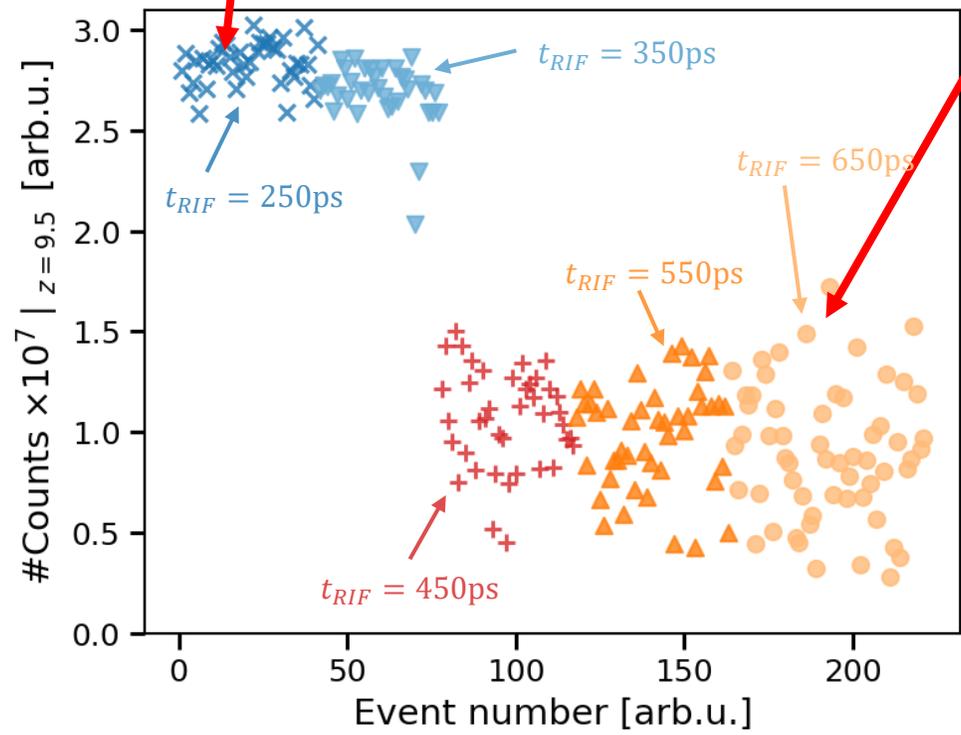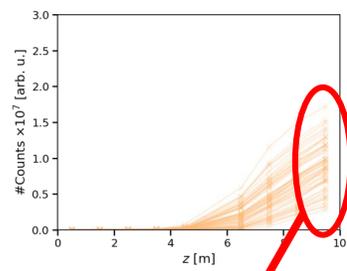- Some outliers, still early in the data analysis (variations in N_b, alignment, camera acquisition...)

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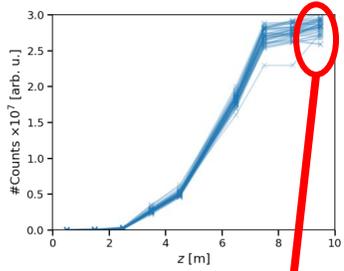- Some outliers, still early in the data analysis (variations in N_b, alignment, camera acquisition...)
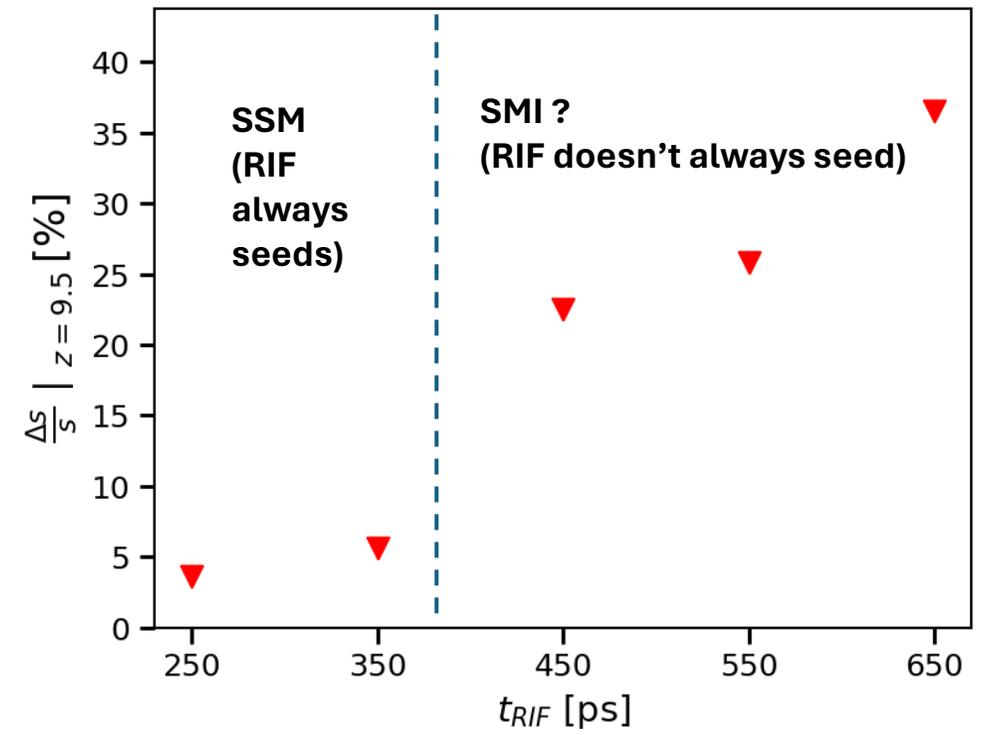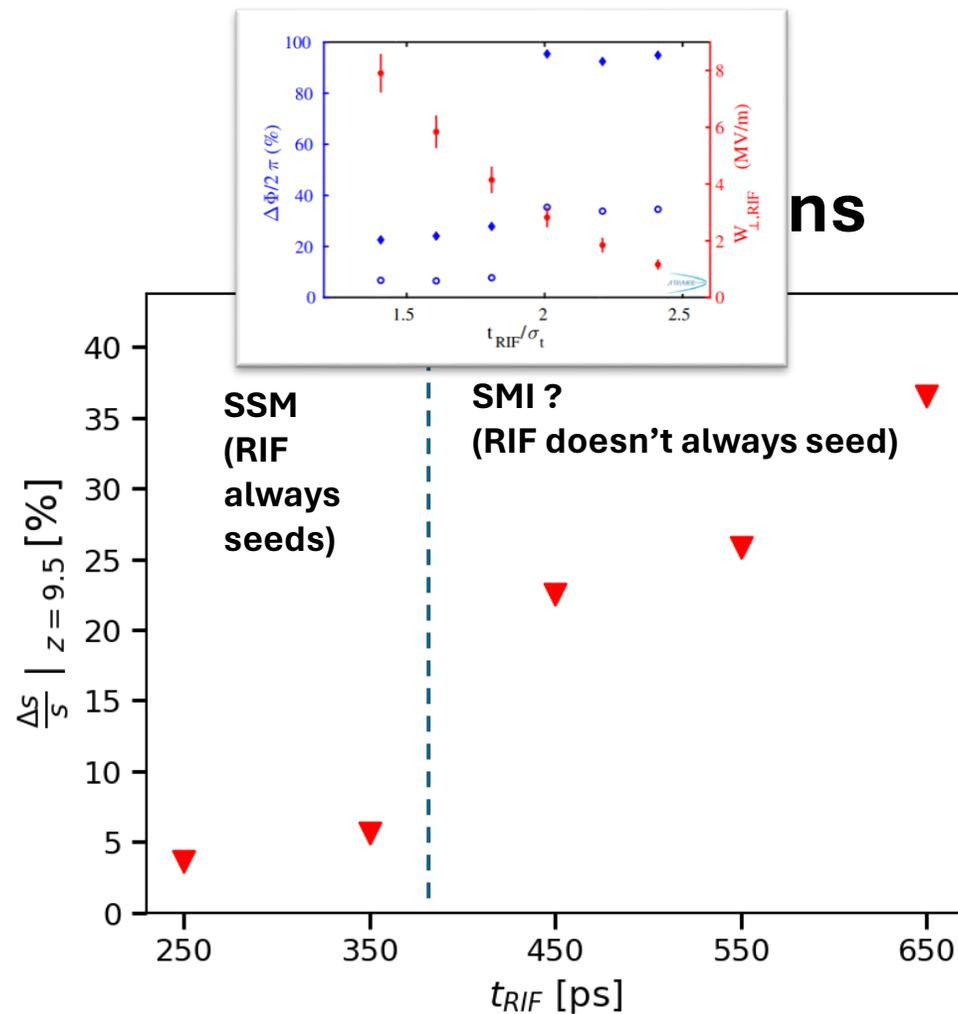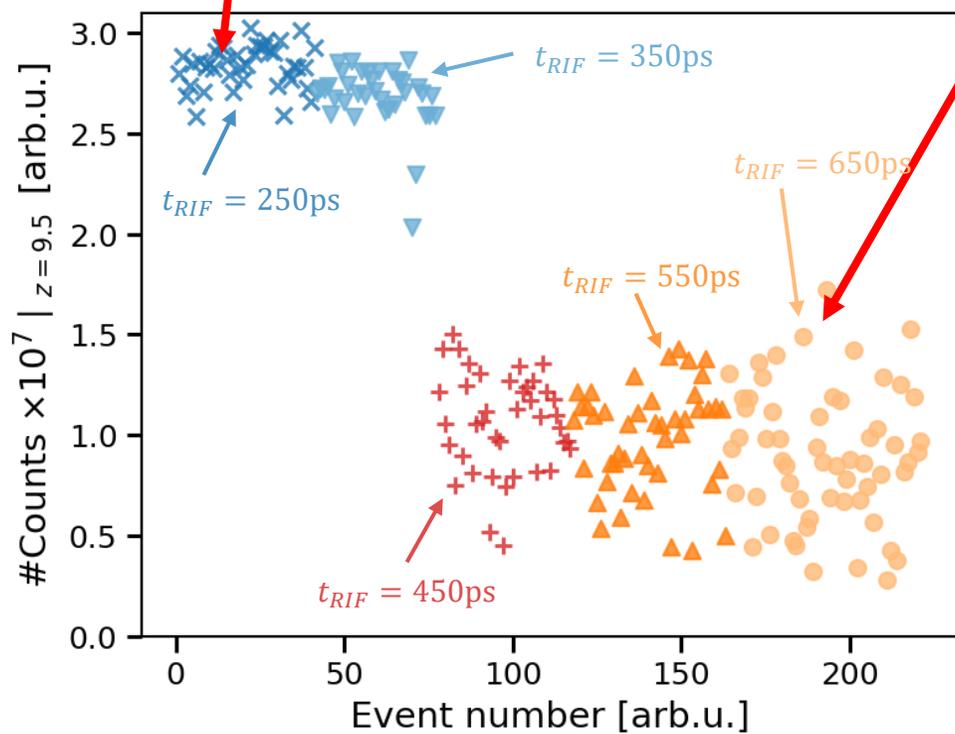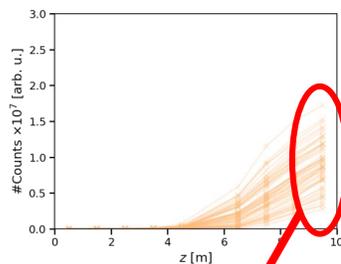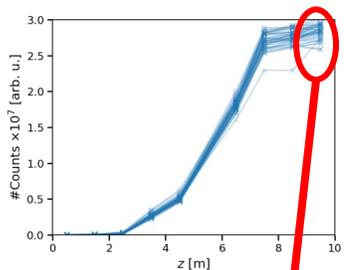
Plasma light, SSM and SMI

Relative variations

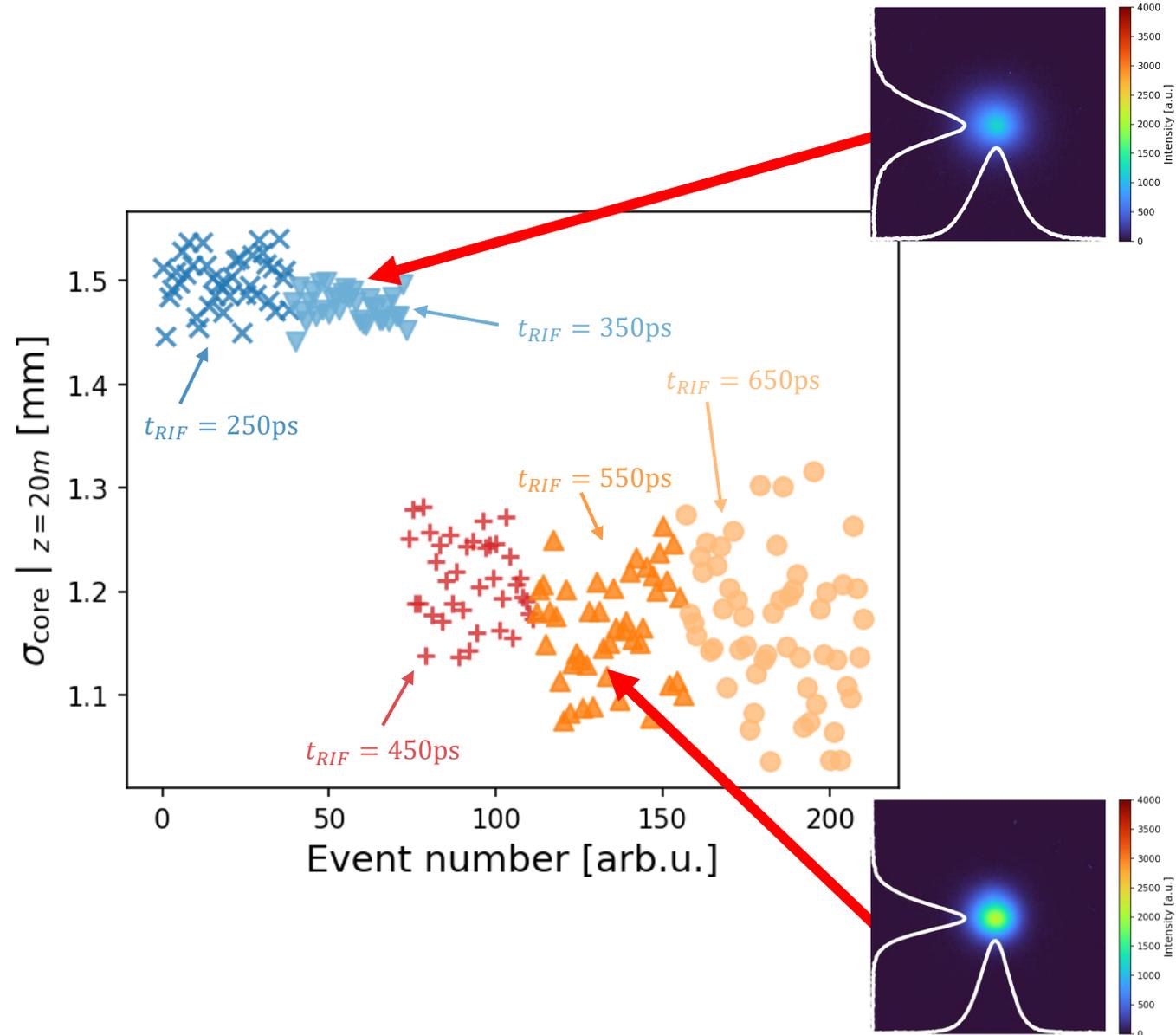# Plasma light, SSM and SMI

Plasma light, SSM and SMI

Transverse profile of the bunch

- Transverse profile of the bunch at IS2
- Wakefield amplitude is small ($N_b = 5 \times 10^{10}$ p+)
- No clear halo formed
- But... still defocusing

- Measure σ_r at IS2
- Again, more variations in SSM than SMI

- Question: Do these variations correlate with those seen with the plasma light ?

Transverse profile of the bunch

- Clear correlation between light and transverse size variations

- Two independant diagnostics, observe the same variations, larger in SSM than SMI

Variations – SSM/SMI

- Transition in amplitude reproducibility occurs at the same t_{RIF} for both plasma light and core size

- More plasma light ⇔ More defocusing

- Correlation between the two quantity strengthens the case of plasma light as a wakefield diagnostic

Conclusions

- Seeding makes timing of microbunches (phase of wakefields) reproducible (Fabian and Livio's PRLs)
- No evidence so far that seeding also makes the amplitude of the wakefields more reproducible

- Reproducible wakefield amplitude is essential for reproducible acceleration, and energy gain

- We use two indirect wakefield diagnostics
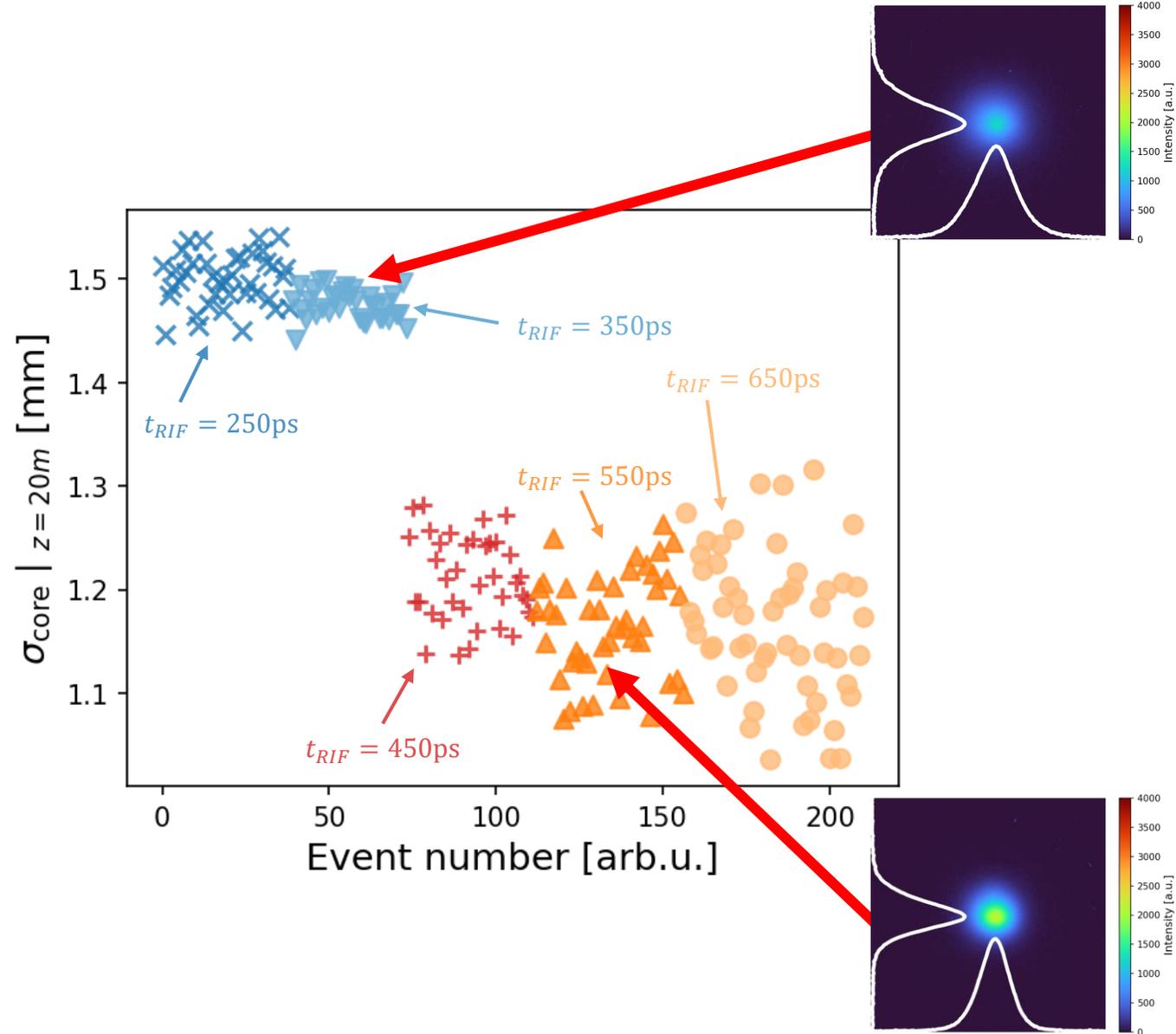 - Plasma light emitted by wakefield dissipation
  - Transverse profile of the bunch

- Both of these diagnostic show that seeding reduces shot-to-shot variations
- Although independant, show that variations are correlated

- Still early in the data analysis, but promising results, data is very clear, other data sets...

- SM can be seeded
- Seeding means that we provide initial field amplitude larger than those driven by noise or features in the longitudinal distribution
- Fabian and Livio had shown that we can seed SM in AWAKE, either with RIF or with e-
- Here we will discuss the RIF method
- Explain RIF seeding method
- Explain results from Fabian
- Phase reproducibility has been demonstrated but the amplitude remains to be shown
- What does it mean for initial field amplitude, to seed SM
- Diagnostics to measure the amplitude of the wakefields ➔ INDIRECT measurements
    - Plasma light (spacially resolved for low bunch population)
    - Bunch profile (spacially integrated effect)

- Show plasma light along the plasma results for varying RIF
- Clear difference in evolution along the plasma ➔ Consistent with halo measurements SSM SMI previous talk
- Clear difference in amplitude reproducibility
- Let's focus on one camera specifically
- Variations are much larger here in SSM than SMI
- We also observe that the maximum amplitude in SMI never exceeds SSM ➔ Consistent with $W_{0,SMI} < W_{0,SSM}$
- By setting the RIF at different locations, we allow the initial fields to vary from max SMI to either min RIF or min SMI
- Consistent with the data
- We can also plot the std/mean, here the results are extremely clear
- We see that the std in the case of SSM is much smaller ➔ Also includes all the jitters (bunch charge, bunch timing, bunch shape, alignment etc)
- We see in SMI that as we allow for more variations, we get more variations
- To further convince ourselves we can look at another diagnostic, here, because the bunch charge is small, the halo formed by SM development is small, but we can look at the core of the bunch
- Less charge in the center means more defocusing
- We observe the same type of variations, larger in SMI than SSM
- We can also plot one against the other, and this further shows that the light emitted and bunch core defocusing are both signatures of the amplitude of the wakefields
- We can extract the variations (here, no need to compare the two per say, but can compare the transition)
- We can also plot the streak images
- Second data set

- Conclusion: Very eary in the data analysis, but here we observe that seeding makes the amplitude of SM reproducible, key for AWAKE, important for the control of instabilities in plasma
    - We use two independant diagnostics
    - Variations are correlated
    - Larger in SMI than SSM
    - Consistent with streak images