Linear Plasma Wakefields and Seeding for the Self-modulation Instability (SMI)

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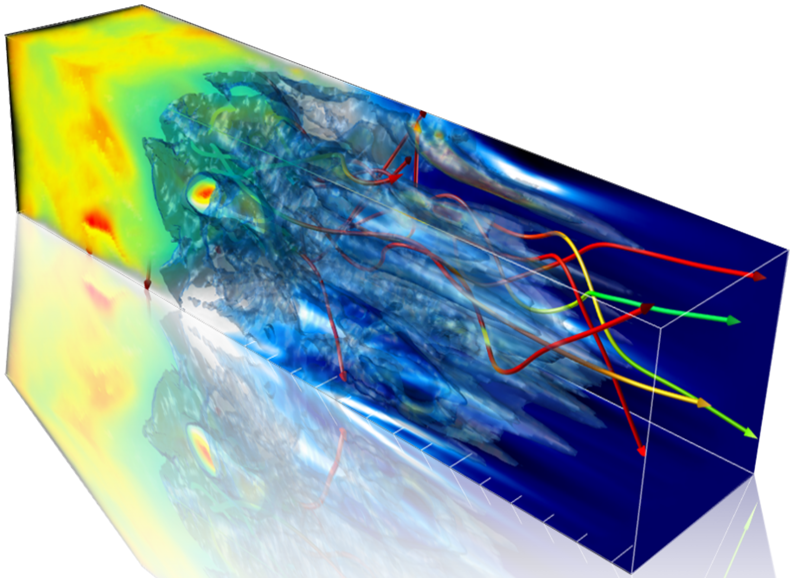
OSIRIS 2.0

osiris v2.0

osiris framework

- Massively Parallel, Fully Relativistic Particle-in-Cell (PIC) Code
- New Hybrid algorithm
- Visualization and Data Analysis Infrastructure
- Developed by the osiris.consortium

⇒ UCLA + IST



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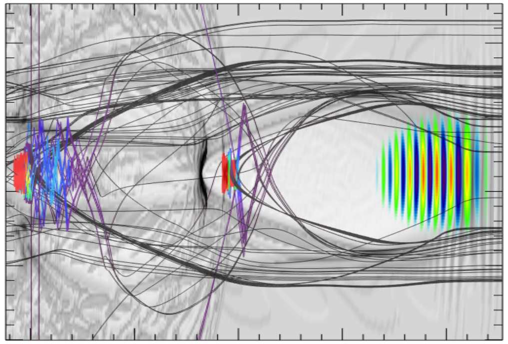
http://cfp.ist.utl.pt/golp/epp/
http://plasmasim.physics.ucla.edu/

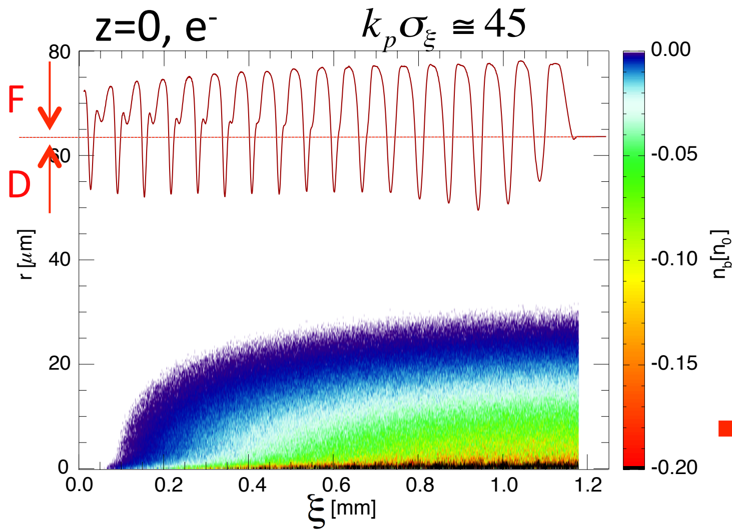


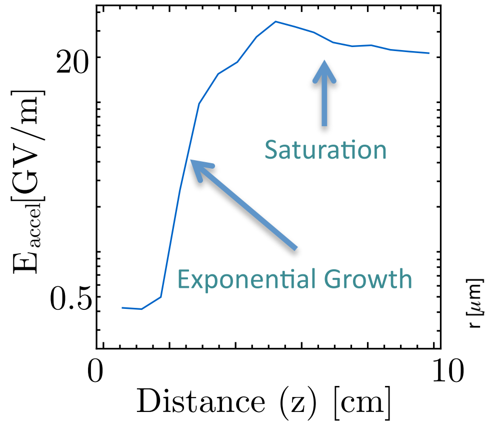
New Features in v2.0

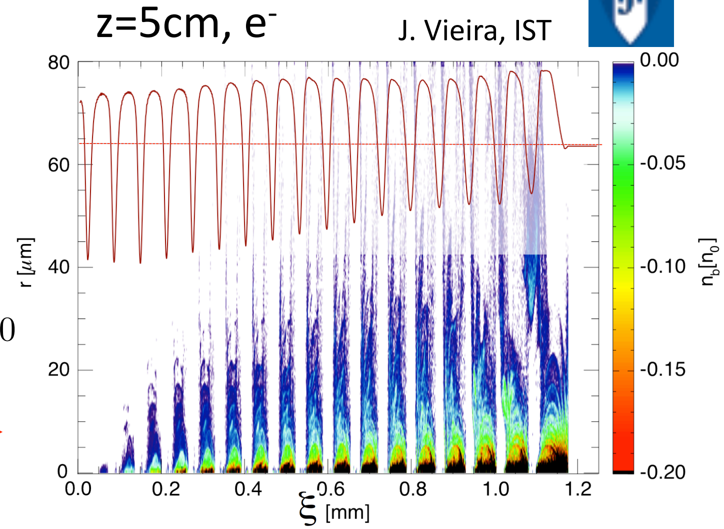
- High-order splines
- Binary Collision Module
- Hybrid code
- Boosted frame
- PML absorbing BC
- Vector processor optimization (SSE)
- Energy and momentum conserving field interpolation
- Higher order and dispersion free solvers
- OpenMP/MPI hybrid
- 3D Dynamic Load Balancing
- Parallel I/O

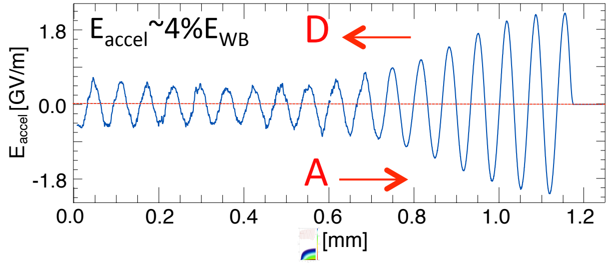
SELF-MODULATiON INSTABiLiTY (SMI)

Kumar, PRL 104, 255003 (2010)

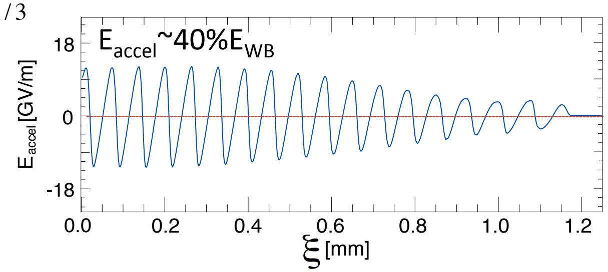








$$N_{\exp} \cong \frac{3\sqrt{3}}{4}\left(\frac{n_b}{n_e}\frac{m_e}{\gamma M_b}\left(k_p|\xi|\right)\left(k_p z\right)^2\right)^{1/3}$$



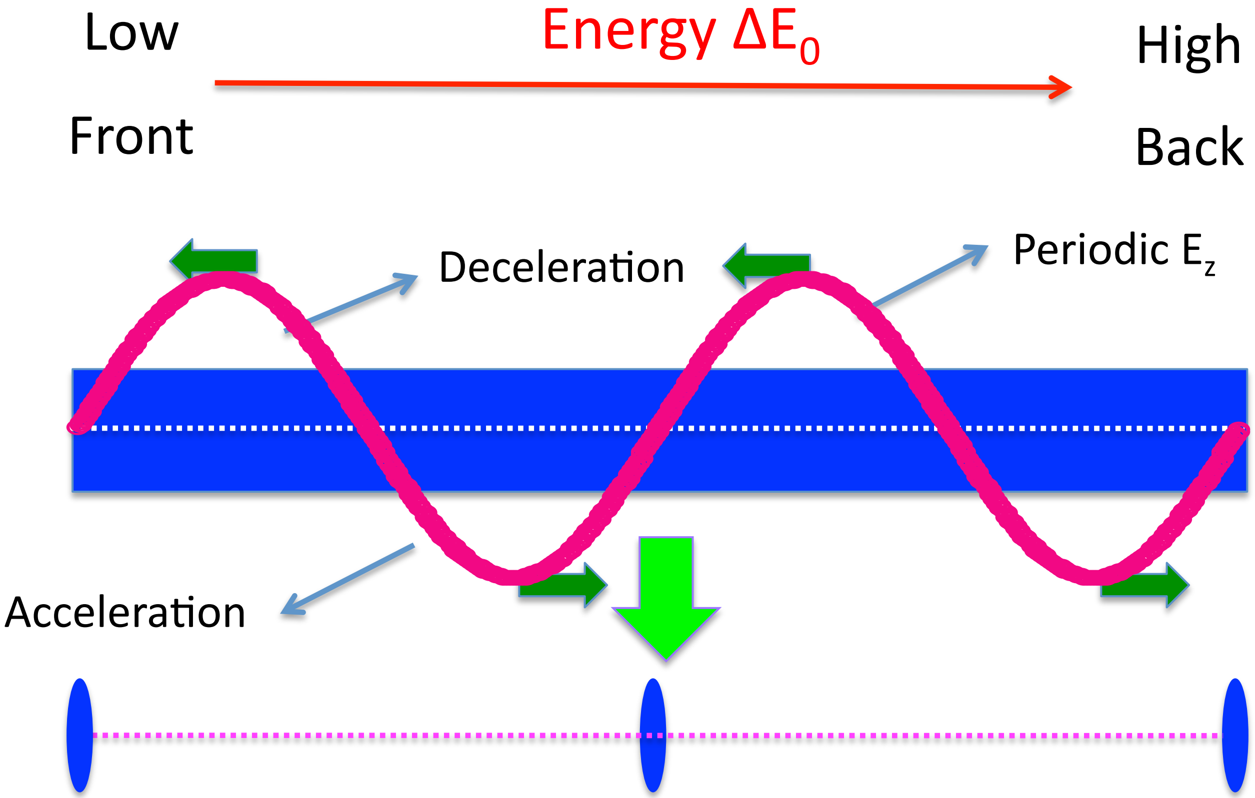
Grows along the bunch & along the plasma
Convective instability

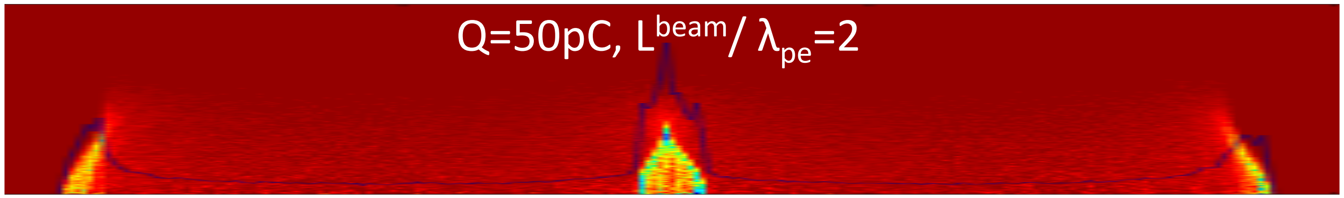
Pukhov, PRL 107, 145003 (2011)
Schroeder, PRL 107, 145002 (2011)

- ✧ Initial small transverse wakefields modulate the bunch density
- ✧ Seeding of SMI important to shorten length to saturation and for wakefield phase for deterministic external injection
- ✧ Longitudinal wakefields can lead to energy (not spatial) modulation

Vieira, Phys. Plasmas 19, 063105 (2012)

Energy Self-Modulation





- ✧ Similar to FEL energy modulation
- ✧ Indirect evidence ($W_{//}=E_z$) of driving of wakefields that can seed the SMI: $W_{perp}=(E_r-cB_\theta)\alpha W_{//}$

Energy Gain/Loss:

$$\Delta E = \frac{1}{4}\cdot\frac{\Delta E_0}{m} \qquad m = L^{beam}/\lambda_{pe} = 1,2,..$$

$$E_z = \frac{1}{4}\cdot\frac{\Delta E_0}{m\cdot eL^{plasma}}$$

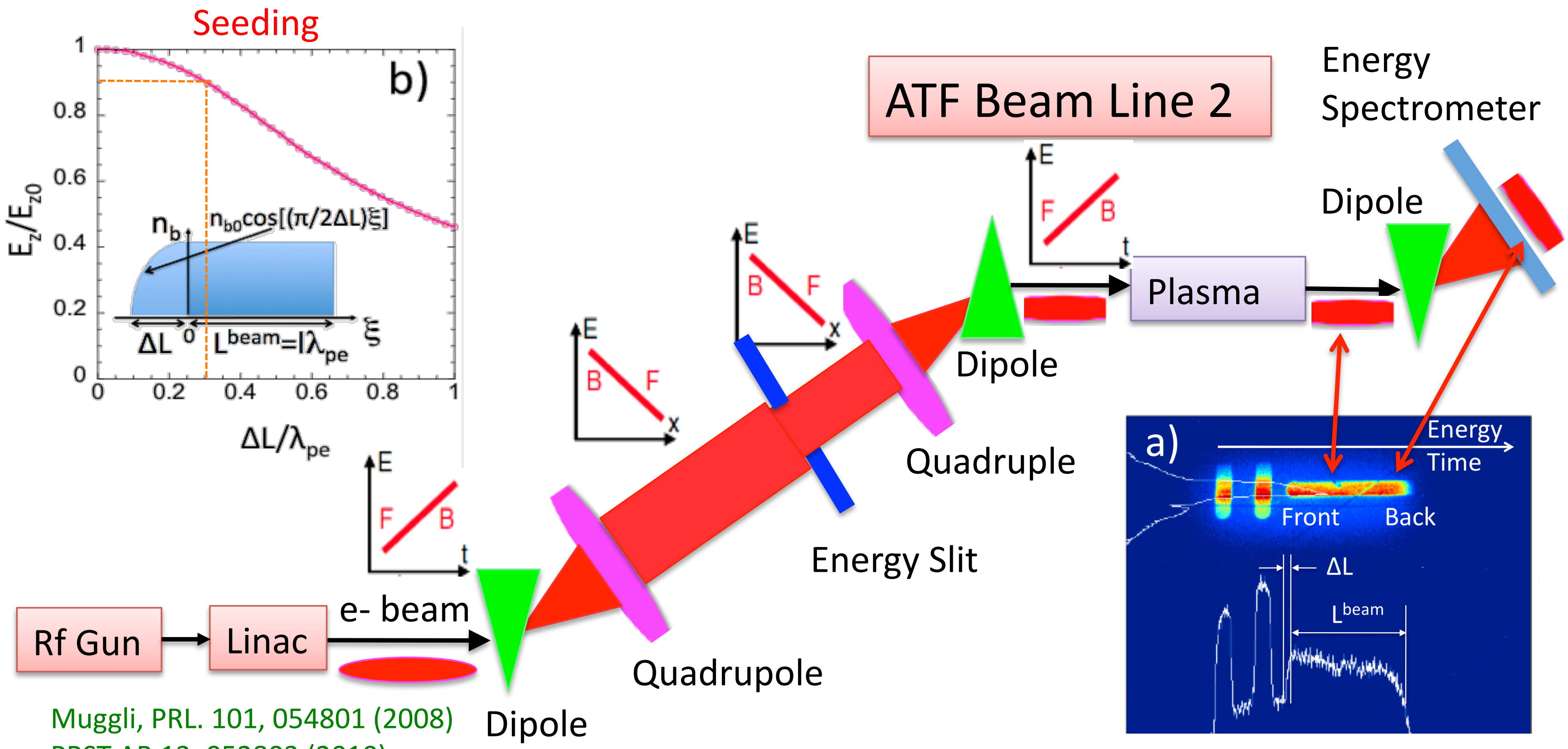
E_z must decreases from ~6 to ~1.2MV/m to preserve visibility! Choose Q=50pC

Linear PWFA theory:

$$E_z(r=0) = \frac{-mQ}{\varepsilon_0 L_b^2 \sigma_r^2}\int_0^\infty e^{-r^2/2\sigma_r^2} K_0(2\pi m/L_b)\, r dr$$

m	$E_{z,\,opt}$ (MV/m)	$E_{z,\,lin,\,OSIRIS}$ (MV/m)	n_e~m^2 (cm^{-3})
1	5.2	3.7	1.2×10^{15}
2	3.0	3.2	4.8×10^{15}
3	2.0	2.6	1.1×10^{16}
4	1.5	2.1	1.9×10^{16}
5	1.2	1.8	3.0×10^{16}

EXPERiMENTAL SETUP



Muggli, PRL. 101, 054801 (2008)
PRST-AB 13, 052803 (2010)

- ✧Use masking method to produce “square” bunch for SMI seeding
- ✧Need cut/step<<λ_{pe}: <0.3λ_{pe} in exp. => E_{z0}>0.9$E_{z0\ sharp}$

EXPERiMENTAL SETUP

Parameter	*Value*
Bunch Energy E_0	$\sim 60\ MeV$
Bunch Charge Q	$50pC - 1nC$
Bunch Focused Size σ_{r0}	$\sim 100\mu m$
Square Bunch Length L_{bunch}	$\sim\ 960\ \mu m$
Normalized Emittance ϵ_N	$\sim 3\ mm - mrad$
Plasma Density n_e	$\sim 10^{14} - 10^{18}\ cm^{-3}$
Plasma Length L^{plasma}	$\sim 2\ cm$
Capillary Radius	$500\ \mu m$

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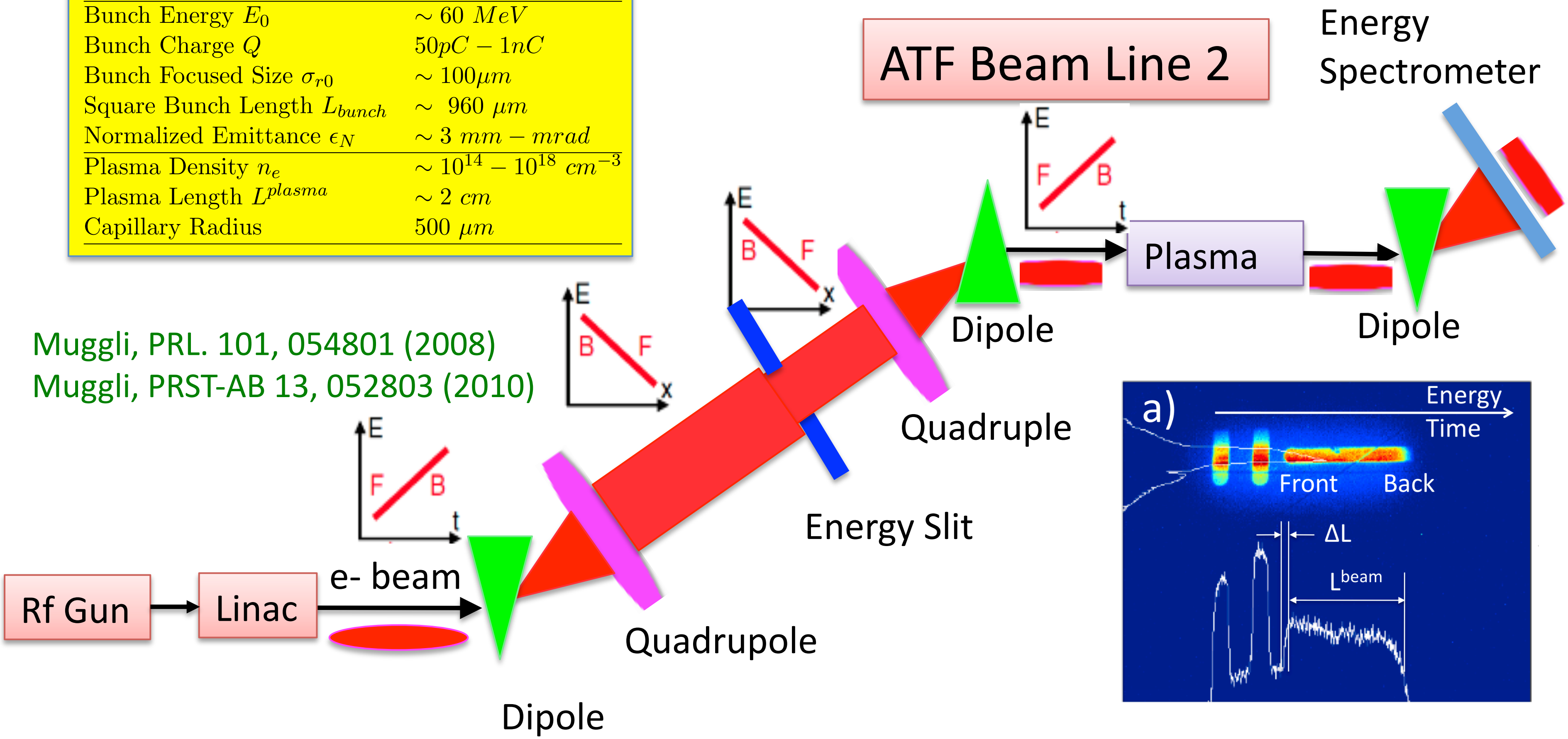

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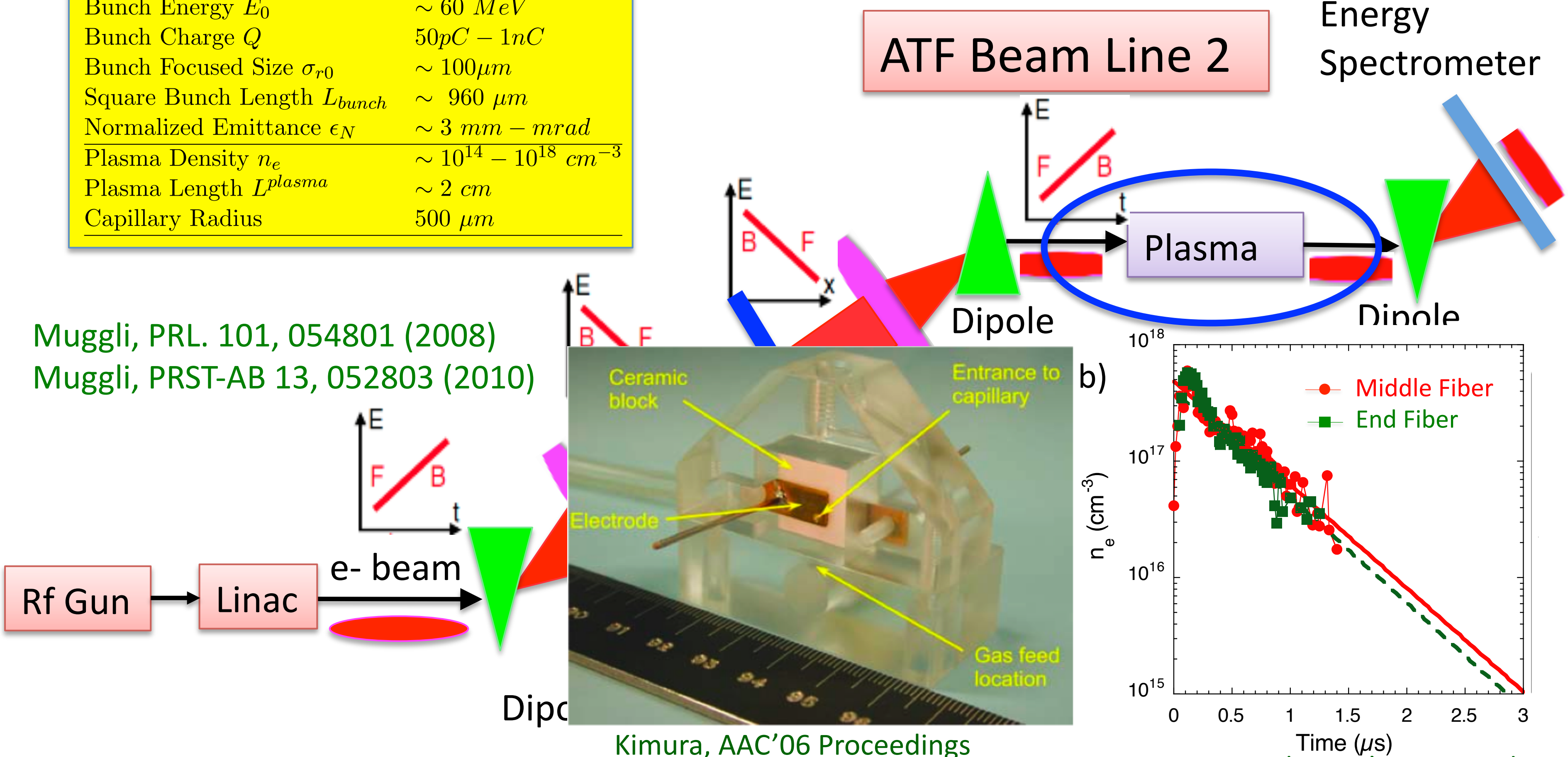

Kimura, AAC'06 Proceedings

Muggli, AAC'10 Proceedings

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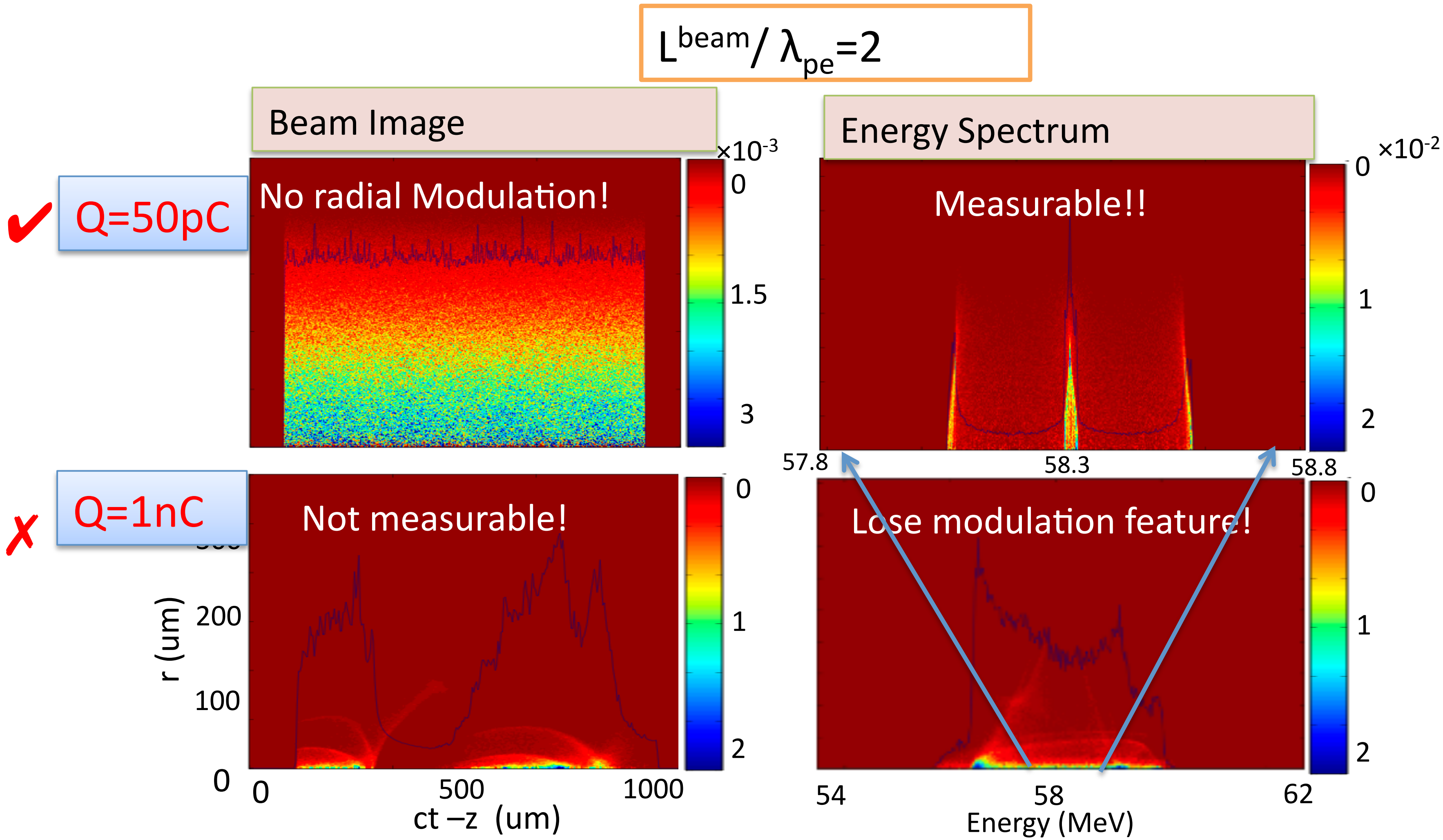
SMI AT HIGH CHARGE

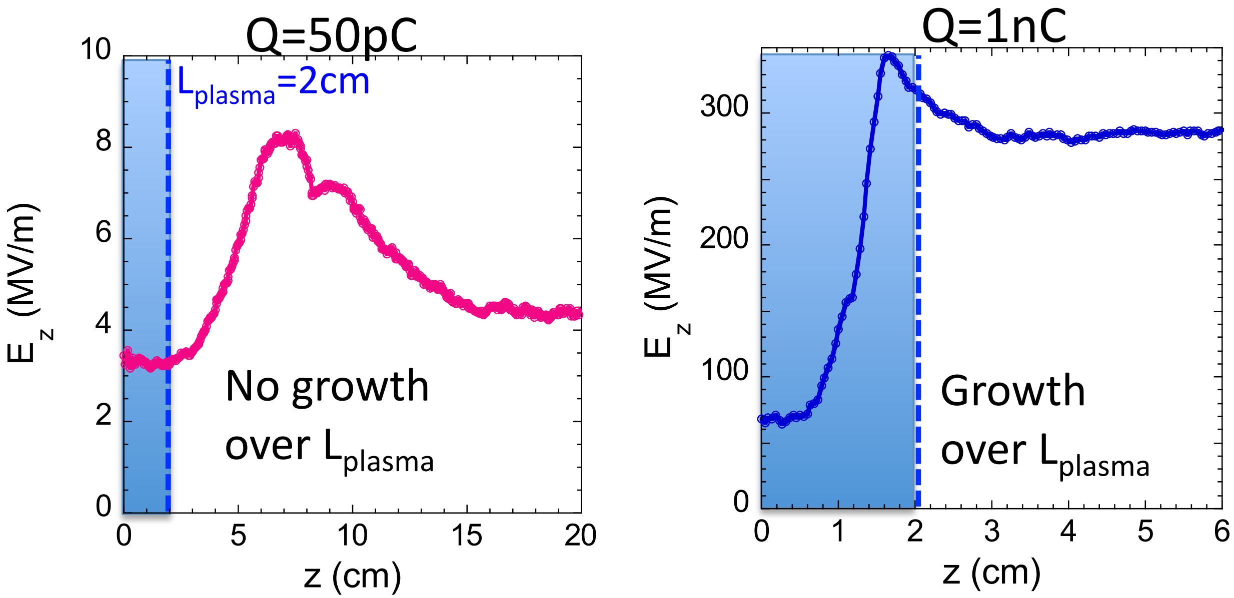


✧Note with 1nC featureless energy spectrum ($\Delta E \gg \Delta E_0$)

✧ Growth from energy gain/loss with high charge (1nC)?

SMI GROWTH?

✧Determine occurrence of SMI growth from energy spectrum $\Delta E >> \Delta E_0$?



✧ Gain=$\int E_+(z)dz = E_0 L_{plasma}$ w/wo SMI growth

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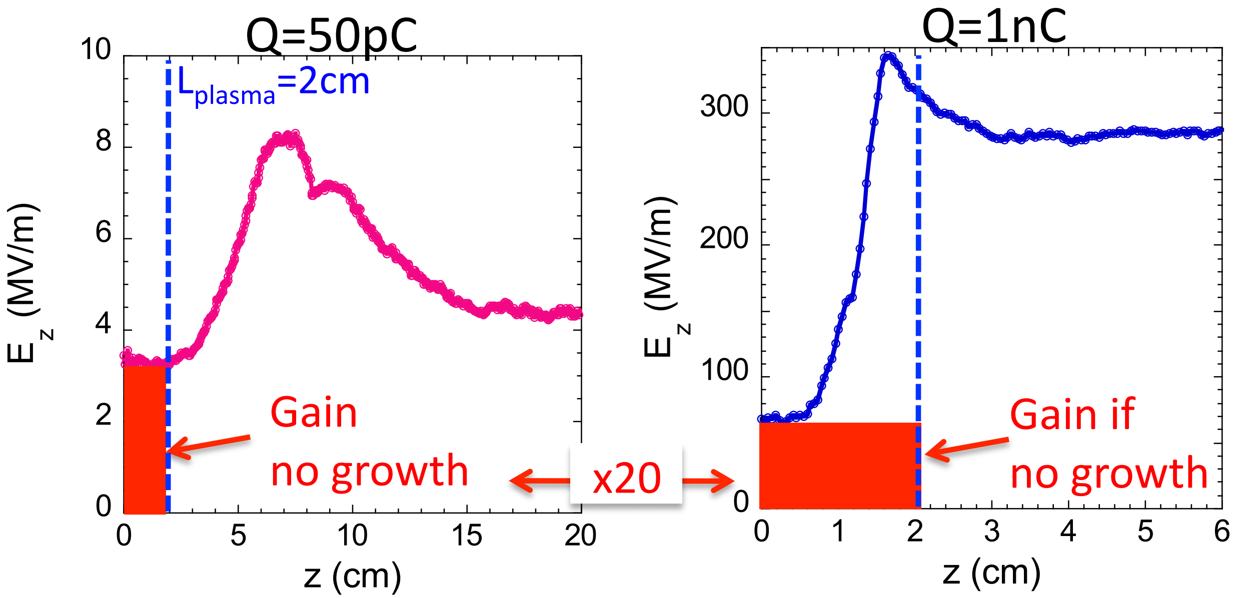

✧ Gain=$\int E_+(z)dz = E_0 L_{plasma}$ w/wo SMI growth

✧ With 50pC $E_0 \approx 3$MV/m, $L_{plasma} \approx 2$cm => Gain≈60KeV < $\Delta E_0 \approx 480$keV => Modulation

✧ With 1nC $E_0 \approx 20*3$MV/m, $L_{plasma} \approx 2$cm => Gain≈1.2MeV without SMI growth

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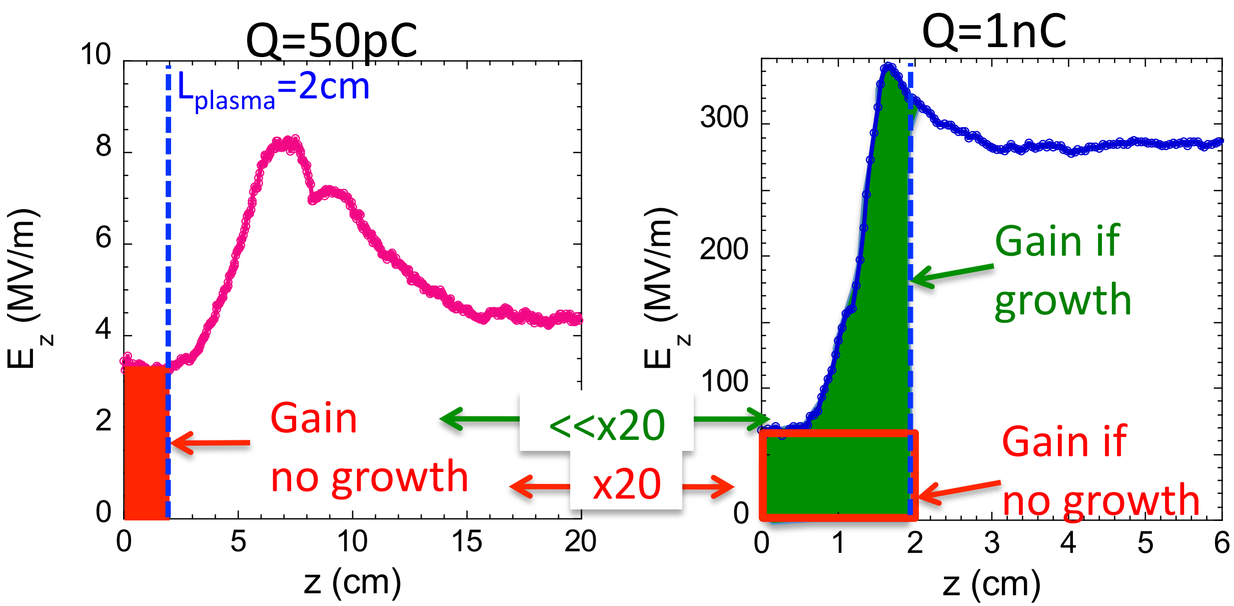

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✧ With 1nC $E_0 \approx 20*3$MV/m, $L_{plasma} \approx 2$cm => Gain≈1.2MeV without SMI growth

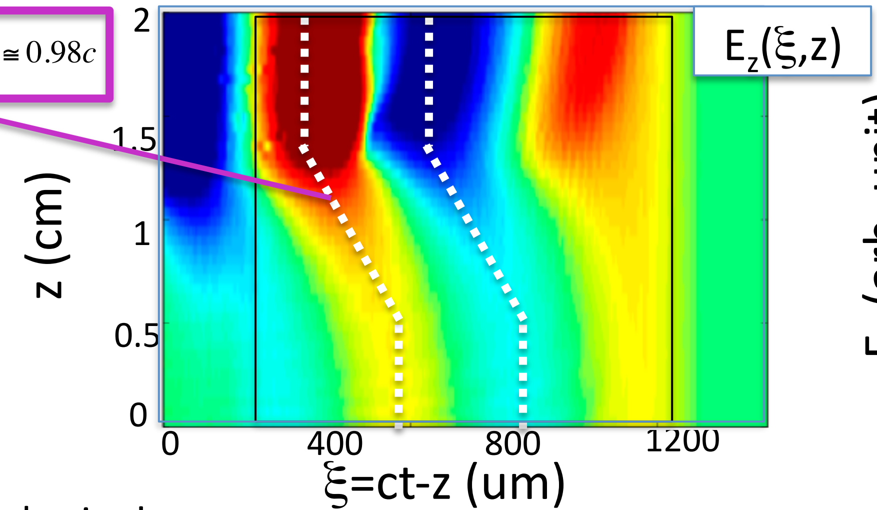
✧ With SMI growth $\int E_+(z)dz > E_0 L_{plasma}$ (Gain ≈2.6 Gain)

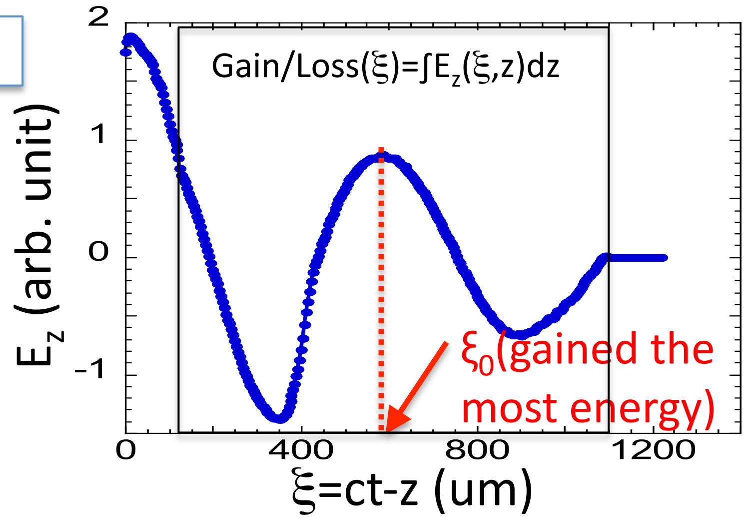
WAKE PHASE VELOCITY

✧ Phase velocity $v_\phi < c$ during SMI growth

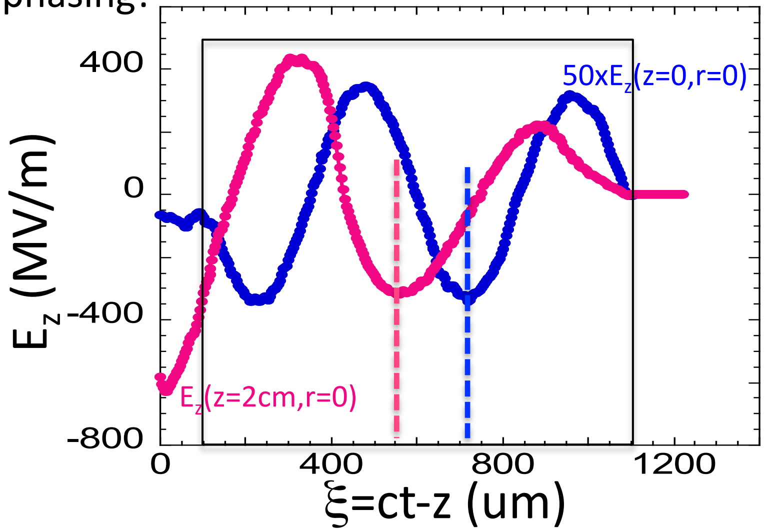
Pukhov, 107, 145003 (2011)
Schroeder, 107, 145002 (2011)

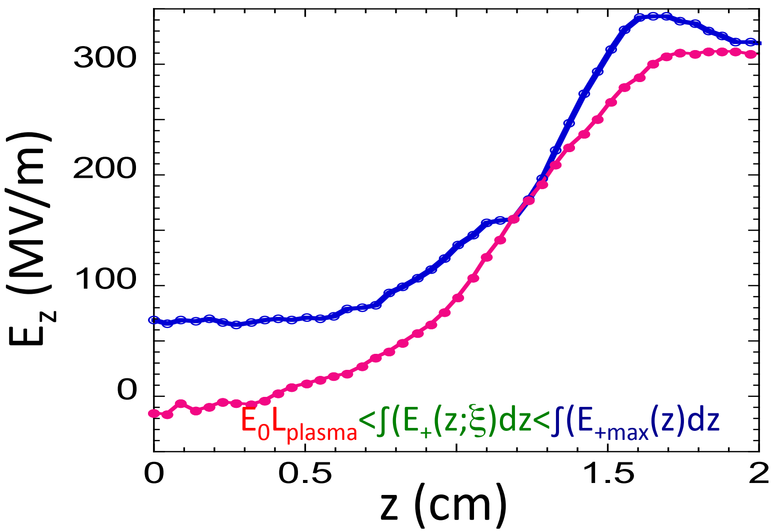
$$v_\phi \cong c\left(1+\frac{1}{dz/d\xi}\right) \cong 0.98c$$





Significant dephasing!

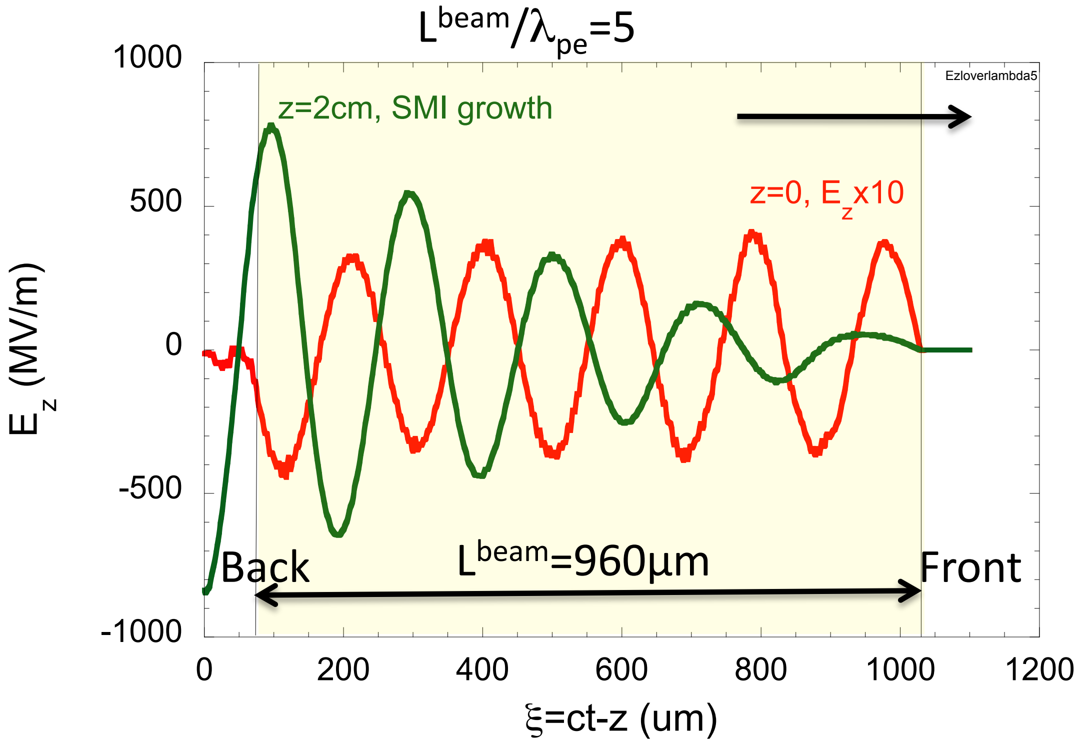


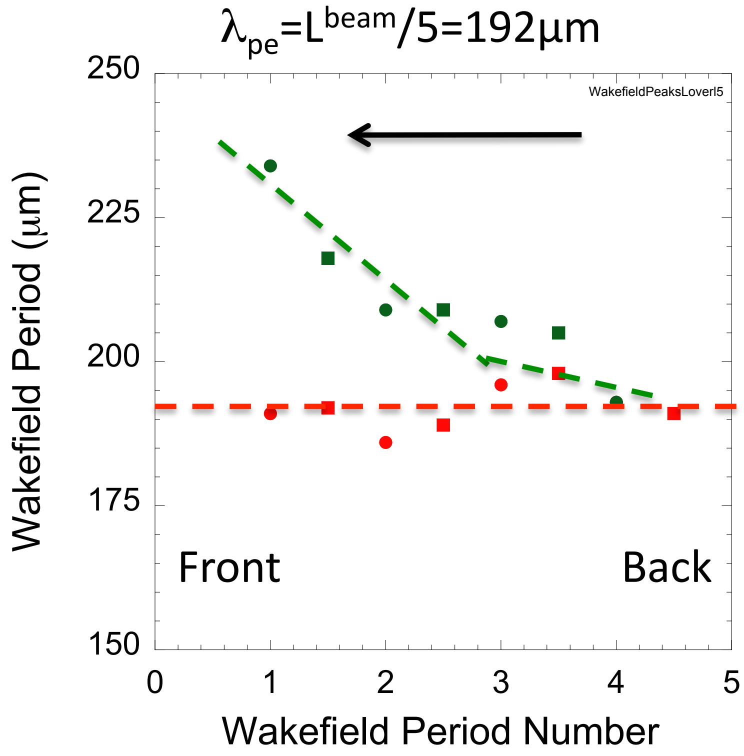


✧ At 1nC $E_0 \approx 20*3$MV/m, $L_{plasma} \approx 2$cm => Gain≈1.2MeV without SMI growth

✧ With SMI growth $\int(E_+(z)dz >> E_0 L_{plasma}$ (Gain ≈2.6 Gain)

WAKEFiELDS DEPHASiNG





✧At saturation the wakefield period is much longer in the bunch front

✧The evolution in the front of the bunch causes the slow wakefields phase velocity …

USC

SUMMARY

MAX-PLANCK-GESELLSCHAFT

- ✧ Shaped, square with $L^{beam} > \lambda_{pe}$ bunches drive linear wakefields with period λ_{pe}
- ✧ Wakefield period observed in energy modulation along chirped bunch with Q=50pC
- ✧ If E_z, $W_{//}$ then $W_{per}=E_r-cB_\theta$ => seed for SMI
- ✧ Looking for evidence of SMI growth from energy spectra in 1nC bunches

THANK YOU!

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