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The Single-Shot Wakefield Measurement System

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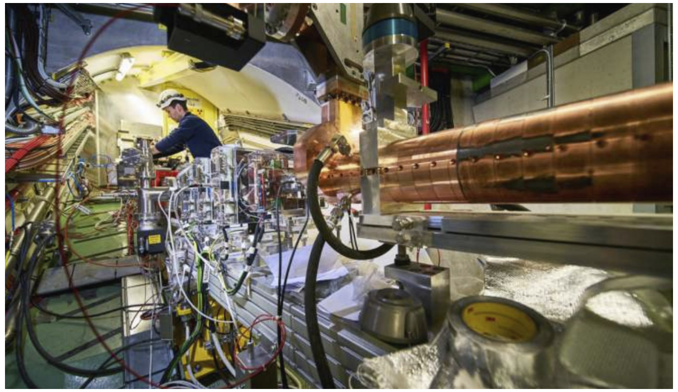
Outline

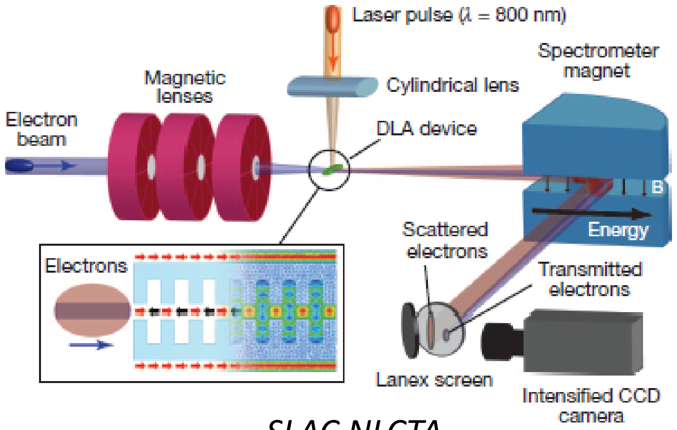
- Introduction and Motivation
- Theory of Single-Shot Wakefield Mapping Method
- Beam Dynamic Simulation
- Experiment Demonstration
- Conclusion

Introduction and Motivation

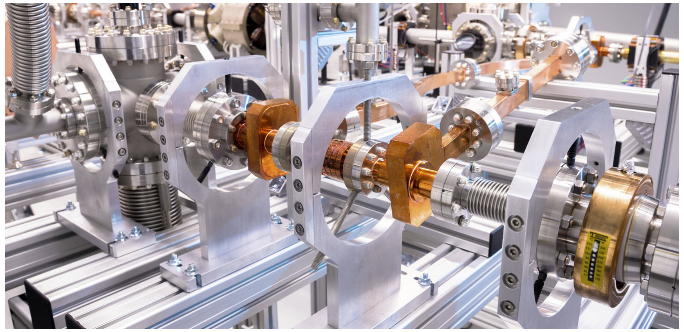
- Wakefield accelerators
  - Driven source
    - Charged beam driven
    - Laser driven
  - Acceleration structure
    - Dielectric
    - Metallic
    - Plasma
  - Acceleration method
    - Collinear
    - Power extraction
  - Benefit
    - High gradient, potential for future colliders.



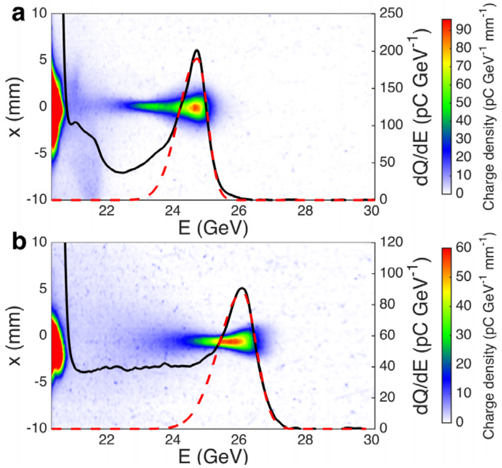
Cern AWAKE



SLAC NLCTA



AWA TBA



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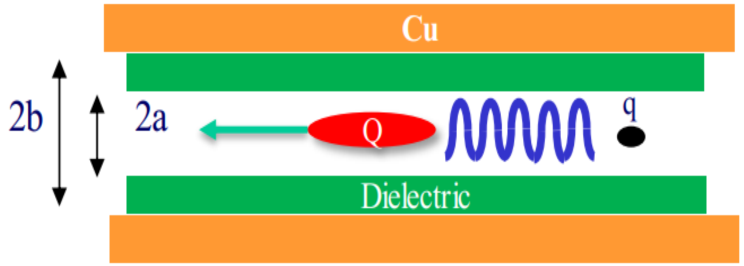
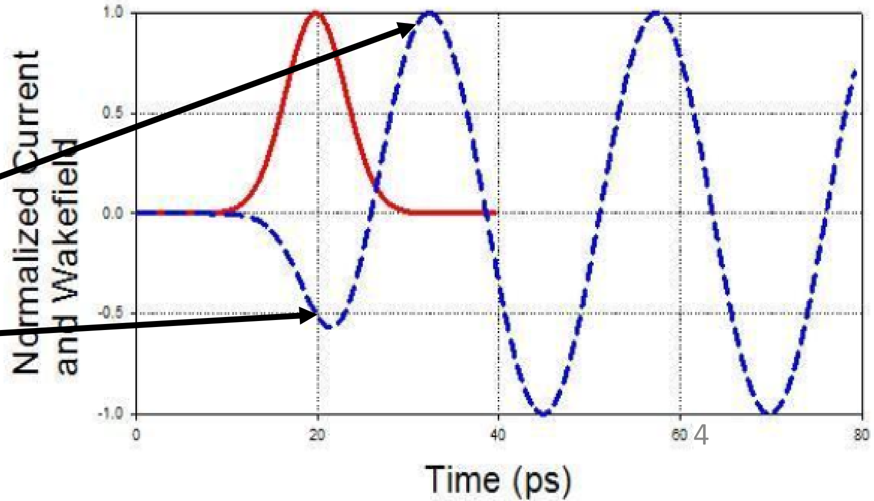
Introduction and Motivation

- Wakefield characteristics
  - Short pulse (~ns).
  - High frequency, up to terahertz.
  - High gradient, up to GV/m.
- How to Measure the wakefield?
  - Gradient?
  - Transformer ratio?
    - The ratio of peak acceleration field behind drive bunch to the peak deceleration field inside drive bunch.
    - determines the maximum energy gain of the witness bunch when the drive bunch loses all of its energy in a CWA scheme.

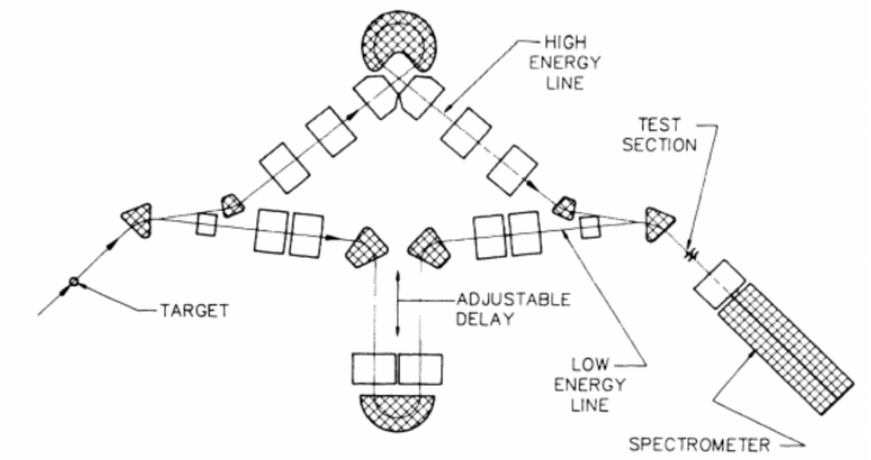


$$TR = \frac{V_{max}^{+}}{V_{max}^{-}}$$

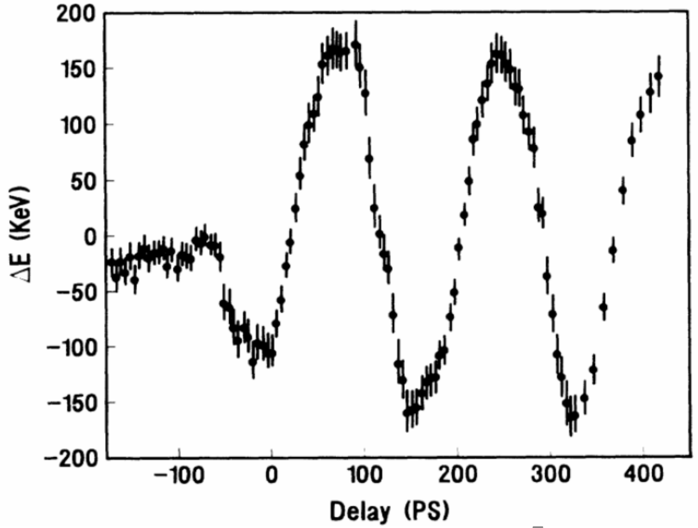


Introduction and Motivation

- Traditional measurement method
  - Low charge, short witness beam with dedicated delay scanning system. The wakefield gradient can be derived from the witness beam energy gain.
  - Two major drawbacks:
    - The duration of witness beam and the jitter of the delay both smear out the wakefield measurement.
    - The short-range wakefield (inside drive bunch) is especially difficult to measure.
- Motivation
  - Develop a more precise/convenient wakefield measurement system without scanning tool.
  - Capability of measuring both the short and long range wakefield.



**Figueroa H, et al. 1988*



Scanning Results

Outline

- Introduction and Motivation
- Theory of Single-Shot Wakefield Mapping Method
- Beam Dynamic Simulation
- Experiment Demonstration
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Theory of Single-Shot Wakefield Mapping Method

- Main idea of single-shot mapping method
  - long witness bunch instead of scanning.
  - longitudinal phase space measurement instead of sole spectrum measurement.
- Long witness bunch and its interaction with wakefield
  - Witness length comparable to one wavelength (region of interest).
  - Energy gain of drive and witness at each time slice represents the wakefield.

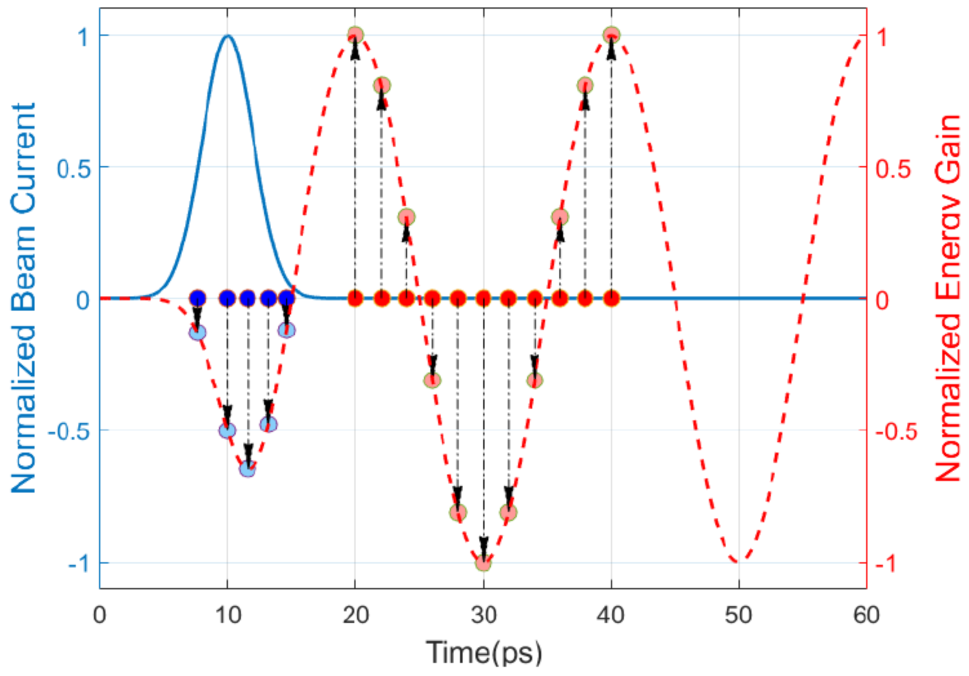
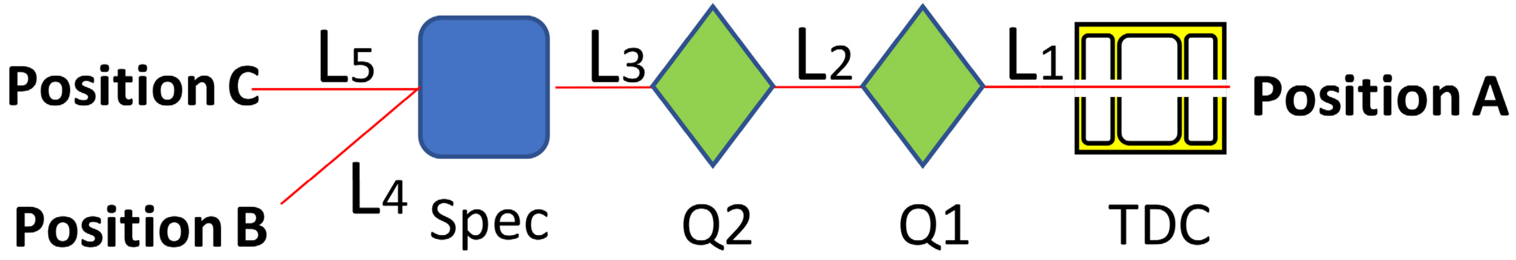


Illustration of the interaction between drive and long witness. Solid blue line indicates the bunch current profile, dashed red line is its wakefield. The navy blue/sky blue dots represent the electrons inside drive bunch with/without wakefield, the cardinal/light red dots are the electron inside a long witness bunch with/without wakefield.

Theory of Single-Shot Wakefield Mapping Method

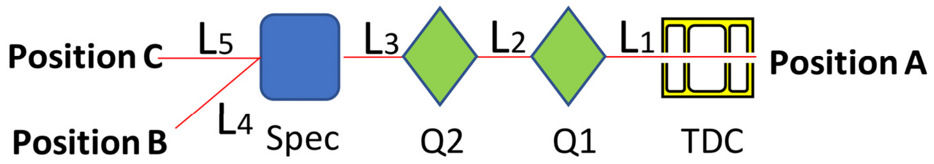
- Longitudinal phase space mapping
  - Spectrometer bends the beam in horizontal direction (x).
  - Transverse deflecting cavity kicks beam in vertical direction (y).
  - Quadrupoles are used to focus the beam to improve the resolution.
  - Energy is projected into x direction and time is projected into y direction.



LPS measurement system layout, Spec, Q, TDC, L stand for spectrometer, quadrupole, transverse deflecting cavity and drift with length L. Position A represents the location at beginning, B and C refer to beam observation stations at bending and straight section after spectrometer, separately.

Theory of Single-Shot Wakefield Mapping Method

- Longitudinal phase space mapping – thin-lens first order beam dynamics



- Transport matrix from A to B:

$$M_{AB} = M_D(L_4) \cdot M_{Sf}(\theta) \cdot M_S(\theta) \cdot M_{Sf}(0) \cdot M_D(L_3) \cdot M_Q(f_2) \cdot M_D(L_2) \cdot M_Q(f_1) \cdot M_D(L_1) \cdot M_T(0)$$

$$= \begin{bmatrix} R_{11_B} & R_{12_B} & R_{13_B} & 0 & 0 & R_{16_B} \\ R_{21_B} & R_{22_B} & R_{23_B} & 0 & 0 & R_{26_B} \\ 0 & 0 & R_{33_B} & R_{34_B} & R_{35_B} & 0 \\ 0 & 0 & R_{43_B} & R_{44_B} & R_{45_B} & 0 \\ R_{51_B} & R_{52_B} & R_{53_B} & 0 & 1 & R_{56_B} \\ 0 & 0 & \kappa & 0 & 0 & 1 \end{bmatrix}$$

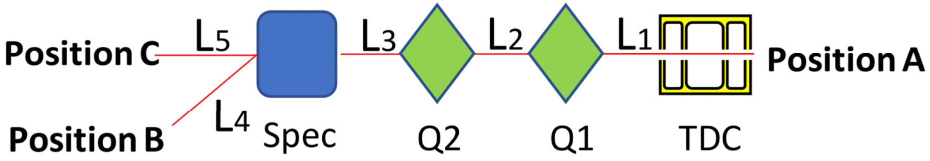
- Projection formula:

$$\begin{cases} x_B = R_{11_B} x_A + R_{12_B} x'_A + R_{13_B} y_A + R_{16_B} \delta_A \\ y_B = R_{33_B} y_A + R_{34_B} y'_A + R_{35_B} z_A \end{cases}$$

- Optimization goal:
  - ✓ Maximize the factor of δ_A and z_A .
  - ✓ Minimize the influence of initial transverse phase space (x_A, x'_A, y_A, y'_A) by Q_1 and Q_2.
  - ✓ R_{13B} and R_{33B} can not be optimized to the minimum value at the same time so that a slit with a small vertical opening is needed to locate at Position A to eliminate the influence of $R_{13B} y_A$.
- How to optimize Q1 and Q2 in practical?

Theory of Single-Shot Wakefield Mapping Method

- Longitudinal phase space mapping – thin-lens first order beam dynamics



- Transport matrix from A to C with TDC and Spec off:

$$M_{AC} = M_D(L_5)\cdot M_D(b)\cdot M_D(L_3)\cdot M_Q(f_2)\cdot M_D(L_2)\cdot M_Q(f_1)\cdot M_D(L_1)$$

$$= \begin{bmatrix} R_{11_C} & R_{12_C} & 0 & 0 & 0 & 0 \\ R_{21_C} & R_{22_C} & 0 & 0 & 0 & 0 \\ 0 & 0 & R_{33_C} & R_{34_C} & 0 & 0 \\ 0 & 0 & R_{43_C} & R_{44_C} & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

- If L_4 and L_5 satisfy the equation:

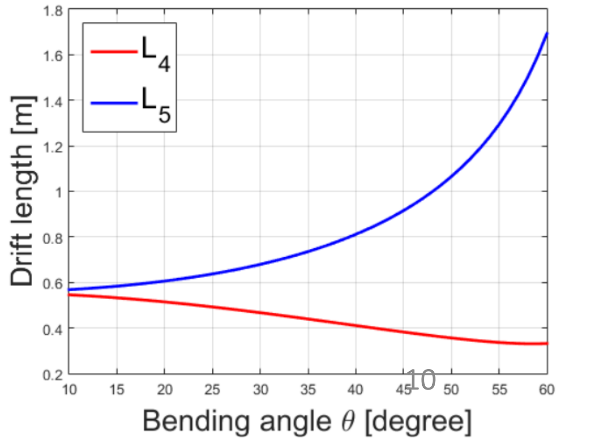
$$\begin{cases} L_5 = \frac{L_4}{\cos^2\theta} + \rho\tan\theta - \rho\sin\theta \\ L_5 = \frac{\rho[\theta\rho + L_4(1-\theta\tan\phi_e)]}{\rho(1-\theta\tan\phi_i) - L_4[\tan\phi_i + \tan\phi_e(1-\theta\tan\phi_i)]} - \rho\sin\theta \end{cases}$$

- Thus,

$$\begin{cases} R_{11_B} = \zeta_x R_{11_C};\ R_{12_B} = \zeta_x R_{12_C} \\ R_{33_B} = \zeta_y R_{33_C};\ R_{34_B} = \zeta_y R_{34_C} \end{cases}$$

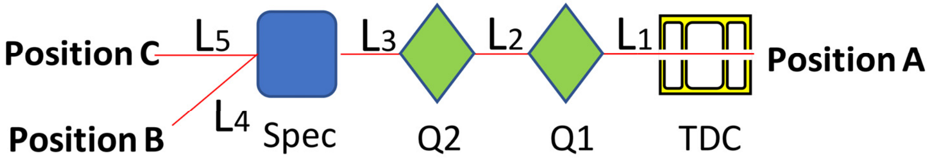
- The equation on the right indicates that no matter how to select the bending angle of spectrometer, once the L_4 and L_5 have the specific relationship, the settings of Q_1 and Q_2 to achieve the smallest beam size at position C, with TDC and SPEC off, is the optimized setting of Q_1 and Q_2 to minimize the initial transverse phase space influence at Position B while TDC and SPEC are on.

$$\begin{cases} \sigma_{x_B}^2 = \boxed{\zeta_x^2\sigma_{x_C}^2} + R_{16_B}^2\sigma_{\delta_A}^2 + R_{13_B}^2\sigma_{y_A}^2 \\ \quad +2R_{11_B}R_{16_B}\sigma_{x_A\delta_A} + 2R_{12_B}R_{16_B}\sigma_{x'_A\delta_A} \\ \quad +2R_{11_B}R_{13_B}\sigma_{x_Ay_A} + 2R_{12_B}R_{13_B}\sigma_{x'_Ay_A} \\ \quad +2R_{13_B}R_{16_B}\sigma_{y_A\delta_A} \\ \sigma_{y_B}^2 = \boxed{\zeta_y^2\sigma_{y_C}^2} + R_{35_B}^2\sigma_{z_A}^2 \\ \quad +2R_{33_B}R_{35_B}\sigma_{y_Az_A} + 2R_{34_B}R_{35_B}\sigma_{y'_Az_A} \end{cases}$$



Theory of Single-Shot Wakefield Mapping Method

- Longitudinal phase space mapping – thick-lens first order beam dynamics



- Considering the non-zero length of TDC and quadrupoles, transport matrix from A to B:

$$M_{AB} = \begin{bmatrix} R_{11_B} & R^*_{12_B} & R_{13_B} & R^*_{14_B} & R^*_{15_B} & R_{16_B} \\ R_{21_B} & R^*_{22_B} & R_{23_B} & R^*_{24_B} & R^*_{25_B} & R_{26_B} \\ 0 & 0 & R_{33_B} & R^*_{34_B} & R^*_{35_B} & 0 \\ 0 & 0 & R_{43_B} & R^*_{44_B} & R^*_{45_B} & 0 \\ R_{51_B} & R^*_{52_B} & R_{53_B} & R^*_{54_B} & R^*_{55_B} & R_{56_B} \\ 0 & 0 & \kappa & \frac{\kappa L_T}{2} & \frac{\kappa^2 L_T}{4} & 1 \end{bmatrix}$$

- Applying the relationship between L_4 and L_5 :

$$\begin{cases} \sigma^2_{x_B} & = \zeta_x^2 \sigma^2_{x_C} + R^2_{13_B}\sigma^2_{y_A} + R^{*2}_{14_B}\sigma^2_{y'_A} + R^{*2}_{15_B}\sigma^2_{z_A} + R^2_{16_B}\sigma^2_{\delta_A} \\ & +2R_{11_B}R_{16_B}\sigma_{x_A\delta_A} + 2R^*_{12_B}R_{16_B}\sigma_{x'_A\delta_A} + 2R_{13_B}R_{16_B}\sigma_{y_A\delta_A} + 2R^*_{14_B}R_{16_B}\sigma_{y'_A\delta_A} \\ & +2R^*_{15_B}R_{16_B}\sigma_{z_A\delta_A} + 2R_{11_B}R^*_{15_B}\sigma_{x_Az_A} + 2R^*_{12_B}R^*_{15_B}\sigma_{x'_Az_A} \\ & +2R_{13_B}R^*_{15_B}\sigma_{y_Az_A} + 2R^*_{14_B}R^*_{15_B}\sigma_{y'_Az_A} + 2R_{11_B}R^*_{14_B}\sigma_{x_Ay'_A} + 2R^*_{12_B}R^*_{14_B}\sigma_{x'_Ay'_A} \\ & +2R_{13_B}R^*_{14_B}\sigma_{y_Ay'_A} + 2R_{11_B}R_{13_B}\sigma_{x_Ay_A} + 2R^*_{12_B}R_{13_B}\sigma_{x'_Ay_A} \\ \sigma^2_{y_B} & = \zeta_y^2\sigma^2_{y_C} + R^{*2}_{35_B}\sigma^2_{z_A} \\ & +2R_{33_B}R^*_{35_B}\sigma_{y_Az_A} + 2R^*_{34_B}R^*_{35_B}\sigma_{y'_Az_A} \end{cases}$$

- The equation above illustrates that:
  - ✓ The energy and temporal resolution is affected by the spectrometer bending angle and deflecting cavity kick strength.
  - ✓ The finite length of deflecting cavity deteriorates the resolution of energy measurement.

Theory of Single-Shot Wakefield Mapping Method

• Longitudinal phase space mapping – thick-lens first order beam dynamics

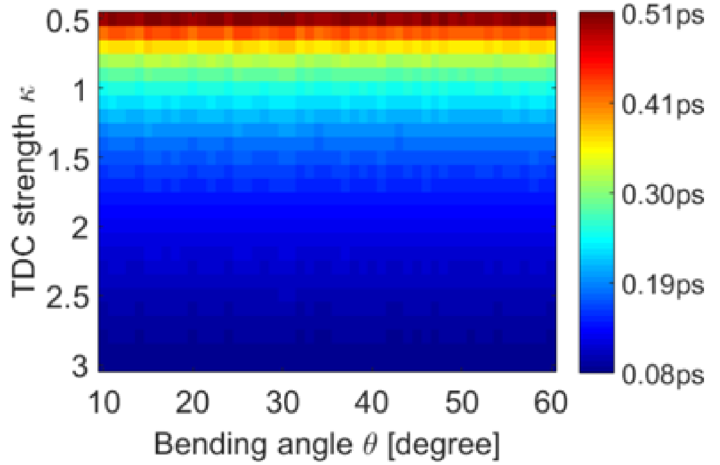
- resolution:

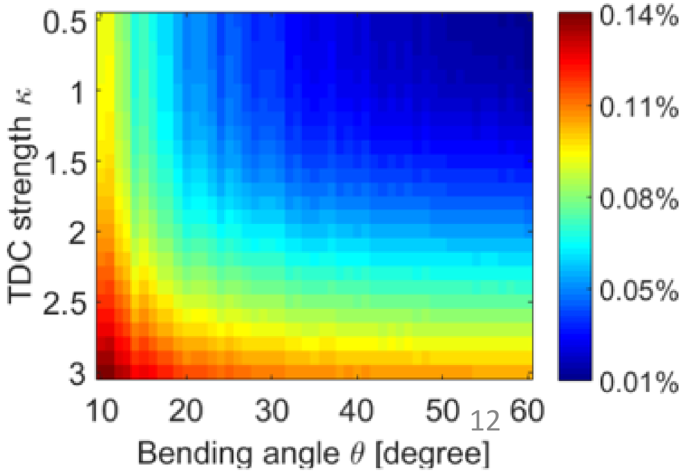
$$\begin{cases} \sigma_\delta &= \dfrac{\sigma_{x_{other}}}{R^*_{16_B}} \\ \sigma_t &= \dfrac{\sigma_{y_{other}}}{v_c R^*_{35_B}} \end{cases}$$

- "Other" refer to the terms contributing to the beam size other than energy or time.

$$\begin{cases} \sigma^2_{x_{other}} &= \zeta_x^2 \sigma^2_{x_C} \\ & +R^2_{13_B}\sigma^2_{y_A} + R^{*2}_{14_B}\sigma^2_{y'_A} + R^{*2}_{15_B}\sigma^2_{z_A} \\ & +2R_{11_B}R^*_{15_B}\sigma_{x_A z_A} + 2R^*_{12_B}R^*_{15_B}\sigma_{x'_A z_A} + 2R_{13_B}R^*_{15_B}\sigma_{y_A z_A} + 2R^*_{14_B}R^*_{15_B}\sigma_{y'_A z_A} \\ & +2R_{11_B}R^*_{14_B}\sigma_{x_A y'_A} + 2R^*_{12_B}R^*_{14_B}\sigma_{x'_A y'_A} + 2R_{13_B}R^*_{14_B}\sigma_{y_A y'_A} \\ & +2R_{11_B}R_{13_B}\sigma_{x_A y_A} + 2R^*_{12_B}R_{13_B}\sigma_{x'_A y_A} \\ \sigma^2_{y_{other}} &= \zeta_y^2 \sigma^2_{y_C} \end{cases}$$

- The bending angle θ and deflecting kick strength κ affect the resolution significantly.
- As stated before, a slit with a small vertical opening is needed to eliminate the affection on energy measurement coming from initial vertical phase space.
- Using the beam parameters of Argonne Wakefield Accelerator, the resolution can be numerically calculated.
- For the actual θ and κ of AWA, the resolution of energy and time is 0.06% and 0.124 ps.





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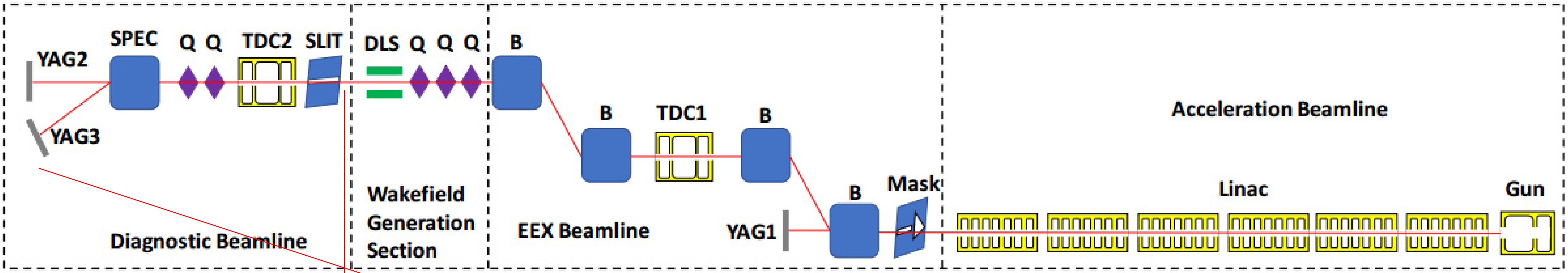
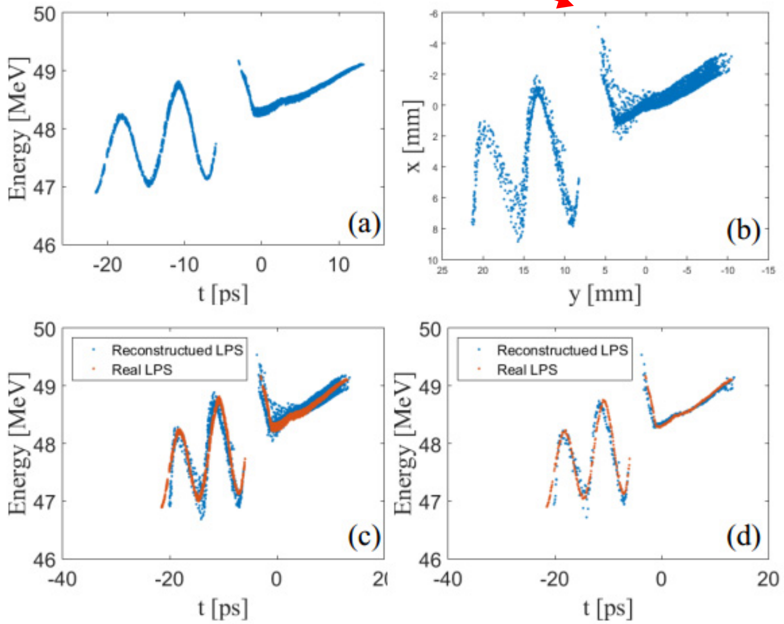
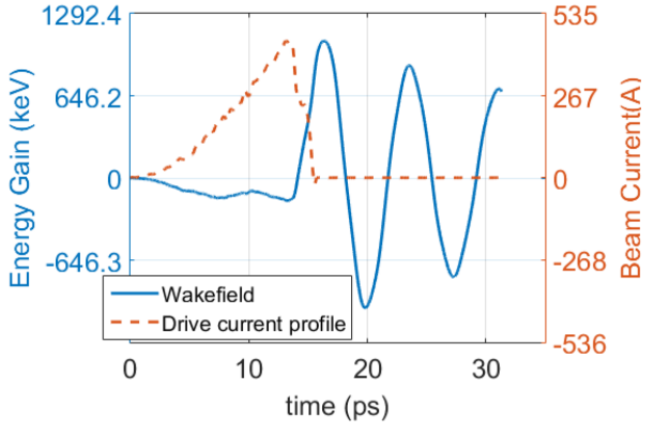
Beam Dynamic Simulation



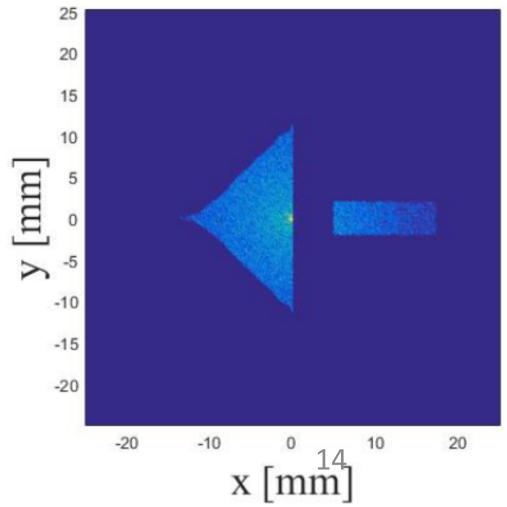
(a)Longitudinal phase space of drive and witness beam behind the wakefield generation section.
(b)x-y plane beam image at YAG3 beam observation station.
(c)Comparison between reconstructed and real LPS.
(d)Comparison of mean LPS profile.



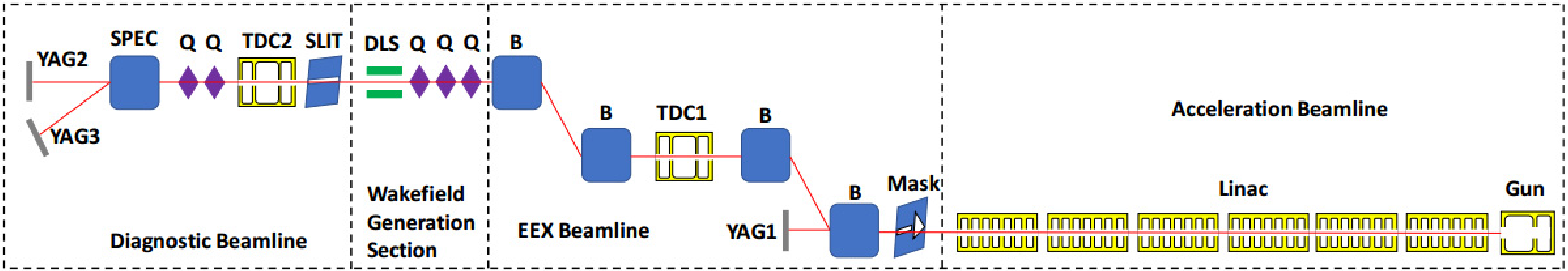
- Drive bunch longitudinal profile and its wakefield in dielectric-lined slab.

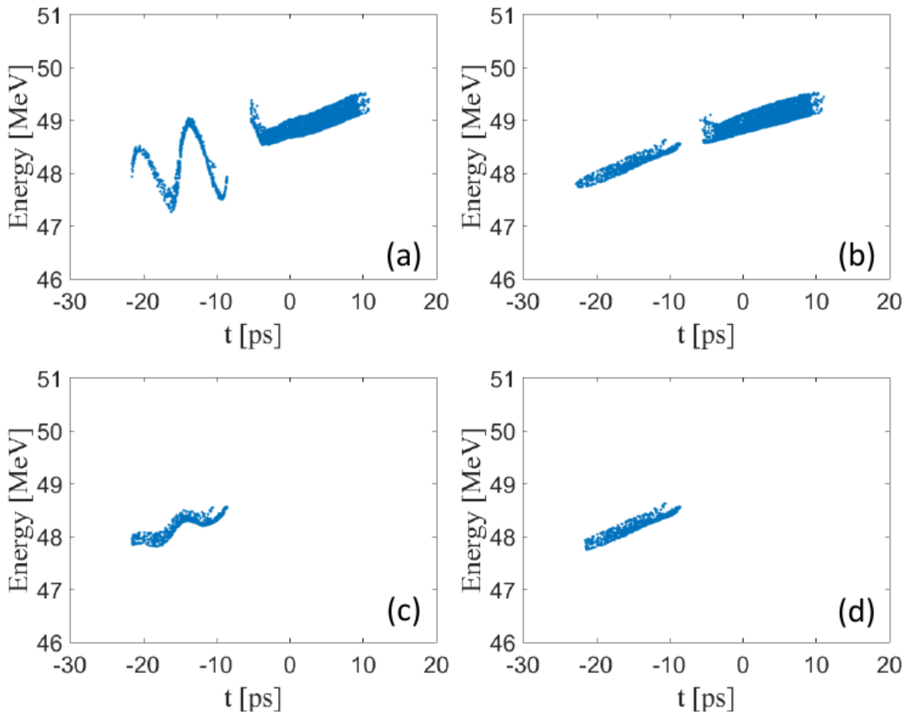


- Beam intercepted by the mask to generate drive bunch and long witness bunch in transverse plane



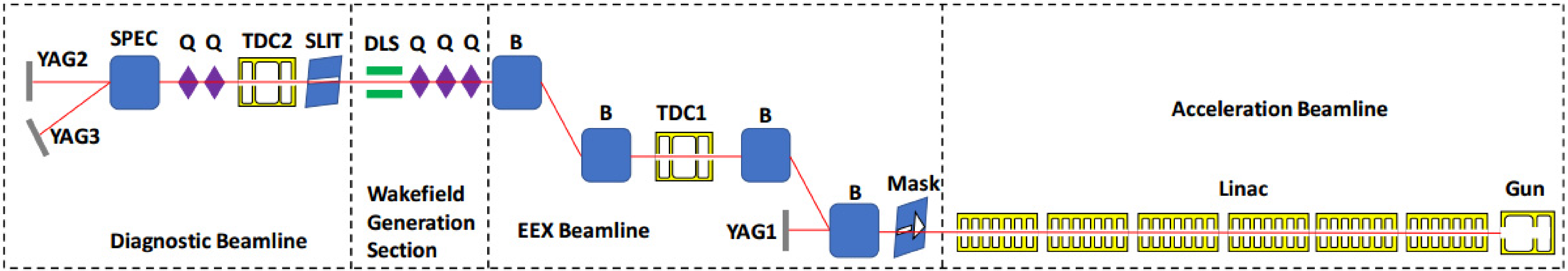
Beam Dynamic Simulation

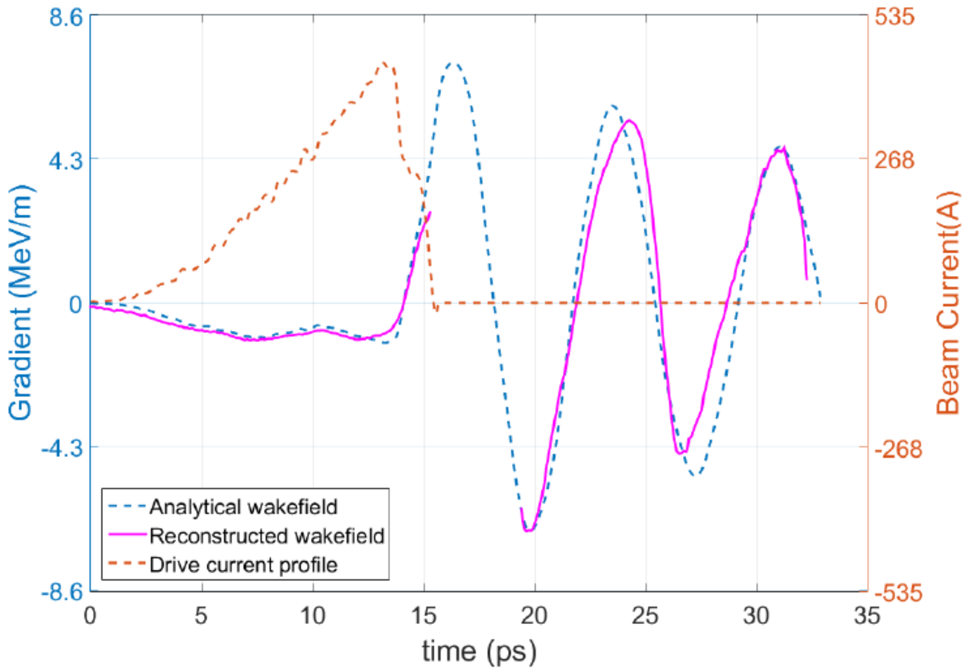




- Wakefield reconstruction method in the simulation:
  - ✓ Take the beam x-y plane image at YAG3 position when the condition is:
    - ➢ (a) both drive and witness beam exist, turn on wakefield effect of the dielectric-lined slab (DLS).
    - ➢ (b) both drive and witness beam exist, turn off wakefield effect of the DLS.
    - ➢ (c) block the drive beam, turn on wakefield effect of the DLS.
    - ➢ (d) block the drive beam, turn off wakefield effect of the DLS.
  - ✓ Take the energy gain between (c) and (d) to derive the self-wakefield of witness beam.
  - ✓ Take the energy gain between (a) and (b) with the subtraction of witness beam self-wakefield, the drive beam wakefield is achieved.

Beam Dynamic Simulation





- Wakefield reconstruction result in simulation:
  - ✓ With the long witness beam and LPS mapping system, the wakefield can be measured by single-shot from beam x-y cross section images.
  - ✓ Both short and long range wakefield information are achieved.
  - ✓ High resolution.

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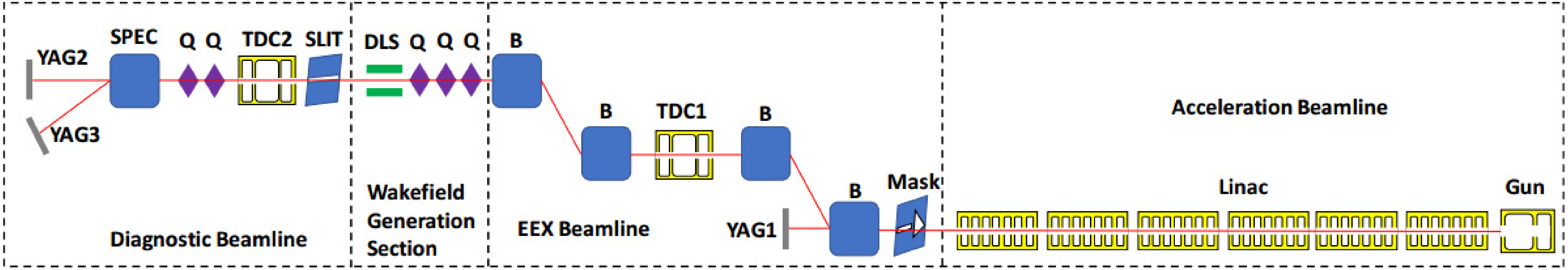
Experiment Demonstration



Diagnostic

- Mapping the longitudinal phase space.

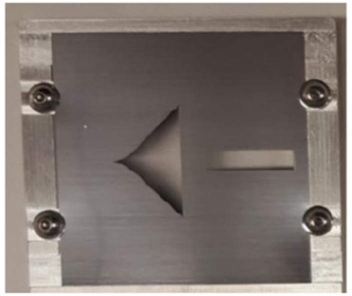
Wakefield Generation Section

- Electron bunch travels through the dielectric-lined slab to excite wakefield.

EEX Beamline

- Exchange the transverse and longitudinal profile of the bunch.

Mask

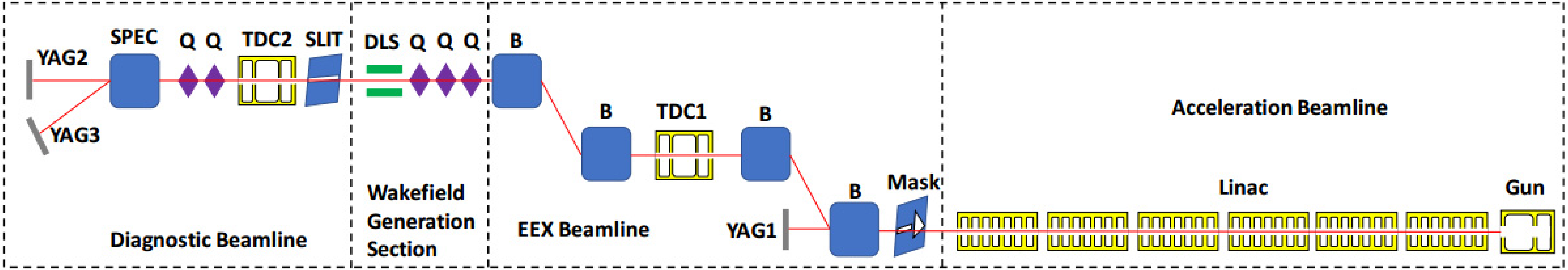


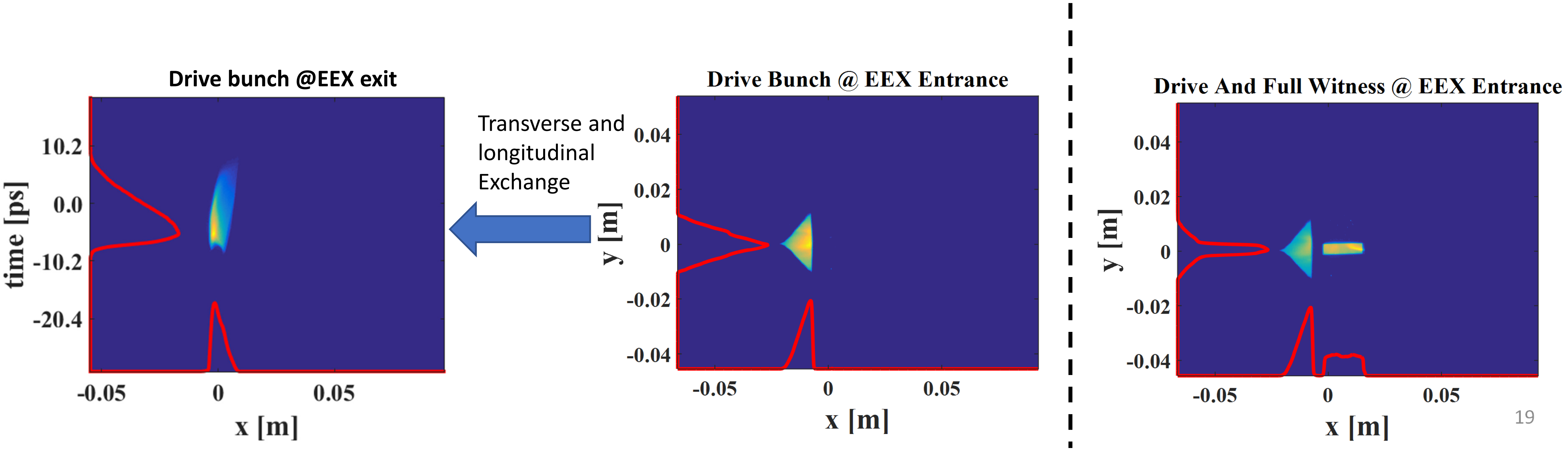
- Tailor the electron bunch transverse phase space

Acceleration Beamline

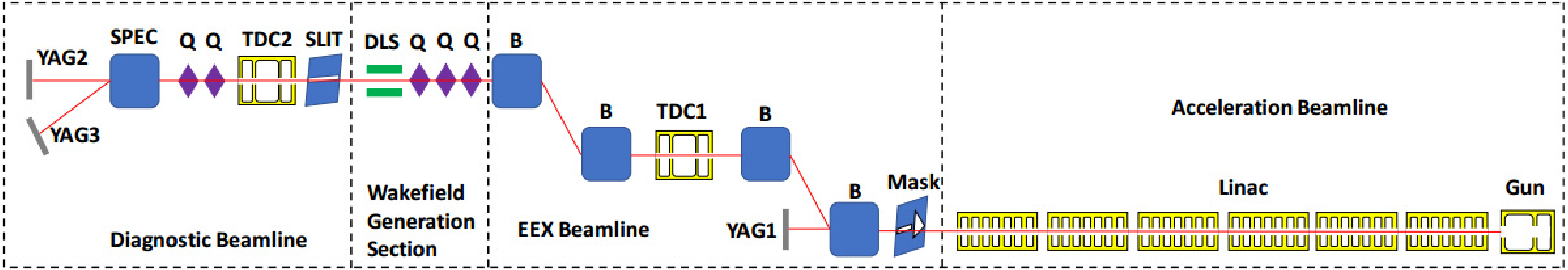
- Photo-injector: Generates a 20-nC, 8 MeV electron bunch.
- Linac: accelerates the bunch to 48 MeV.

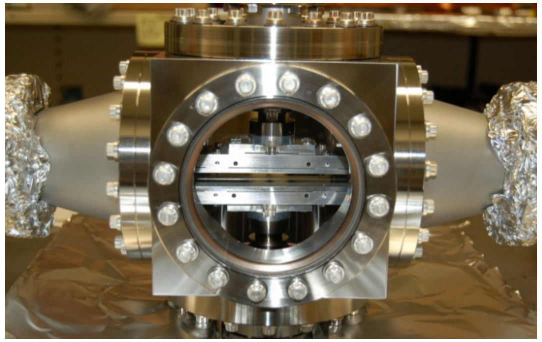
Experiment Demonstration

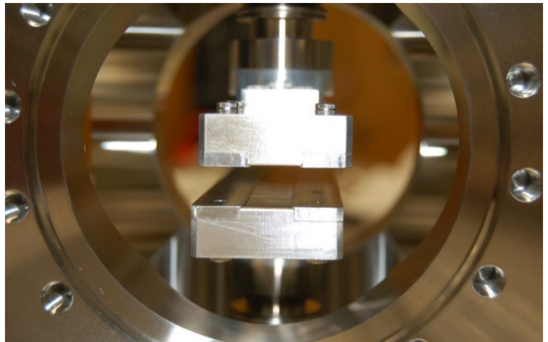




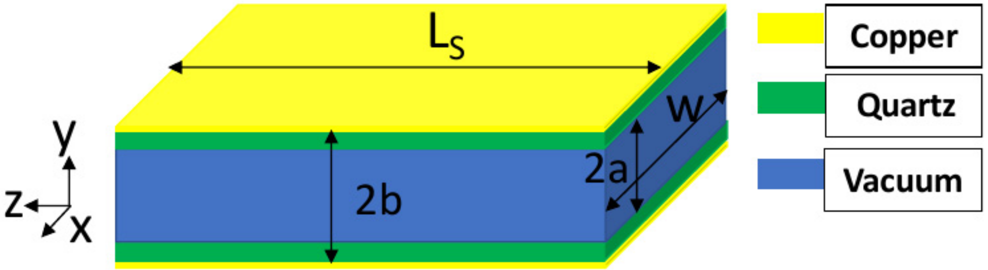
Experiment Demonstration







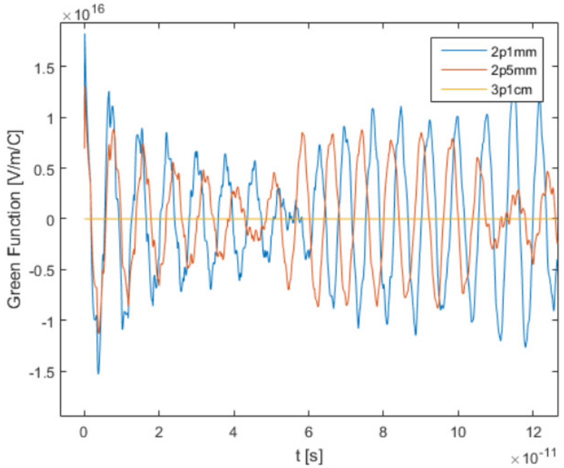
DLS



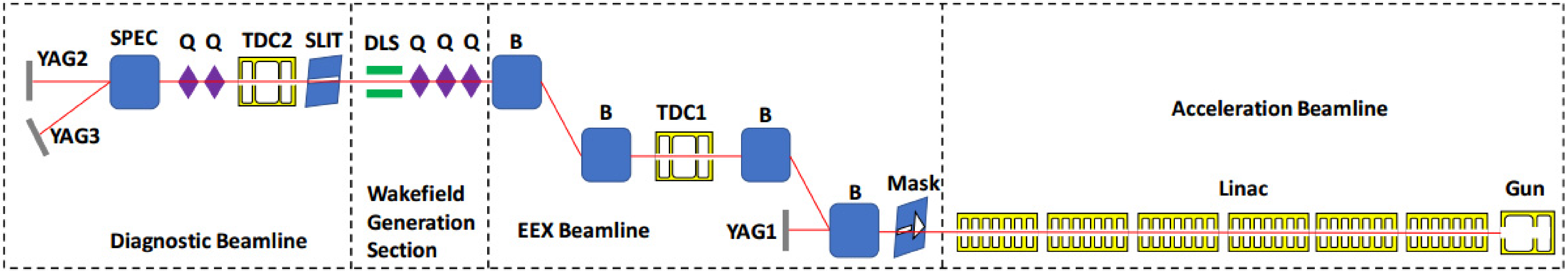
- Quartz, $\epsilon_r = 3.75$, thickness=150 um, length=15cm, width=1.27cm, copper coating.
- Gap between two jaws ranges from 0 to 3.1 cm.
- Fundamental modes: @121.9 and @130.7 GHz.

- Wake function

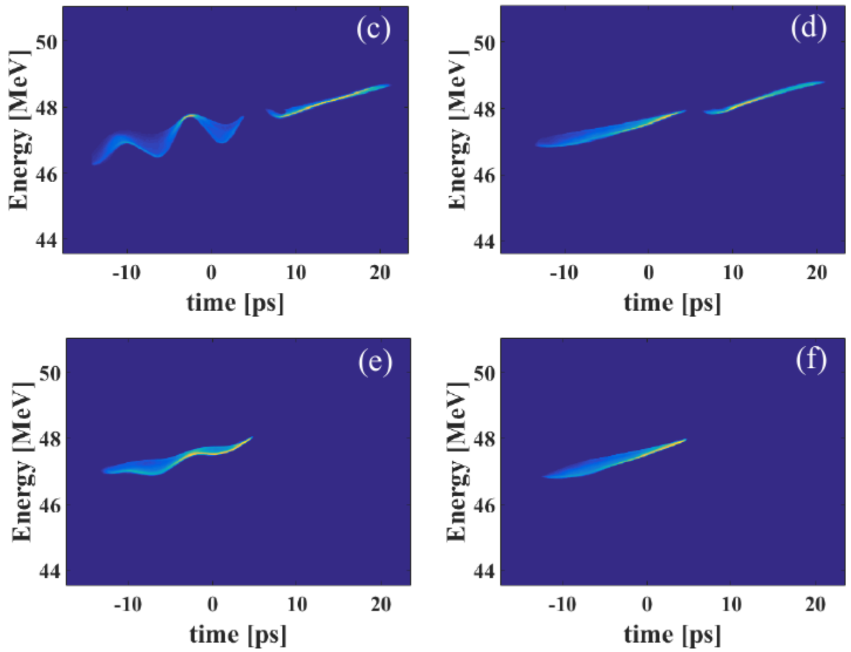
$$G(z) = \sum_{m=1}^{M} \sum_{n=1}^{N} \frac{\omega_{mn}}{4} \left(\frac{R}{Q}\right)_{mn} \frac{1}{1 - v_g/c} \cos \beta_{mn} z$$



Experiment Demonstration

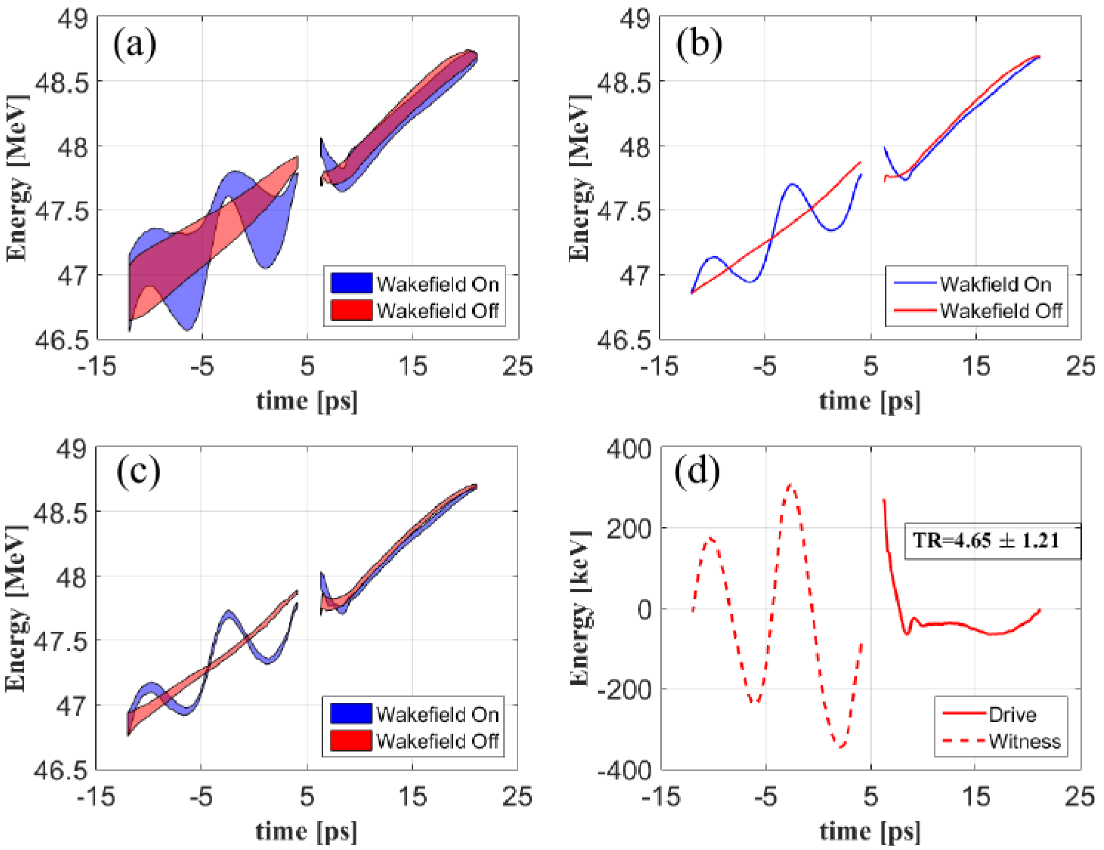


- (c-d) Drive and witness bunch at YAG3 with wakefield on/off.
- (e-f) Witness bunch at YAG3 with wakefield on/off.



- The wakefield can be reconstructed from beam x-y cross section images in four cases.
- Wakefield off indicates the dielectric slab is fully open, and there is no wakefield. Wakefield on represents the structure is closed with a gap 2.5 mm where wakefield is strong.
- Drive bunch is blocked to study the witness beamloading due to its self-wakefield, this beamloading is subtracted from the total energy gain in order to calculate the drive bunch wakefield.

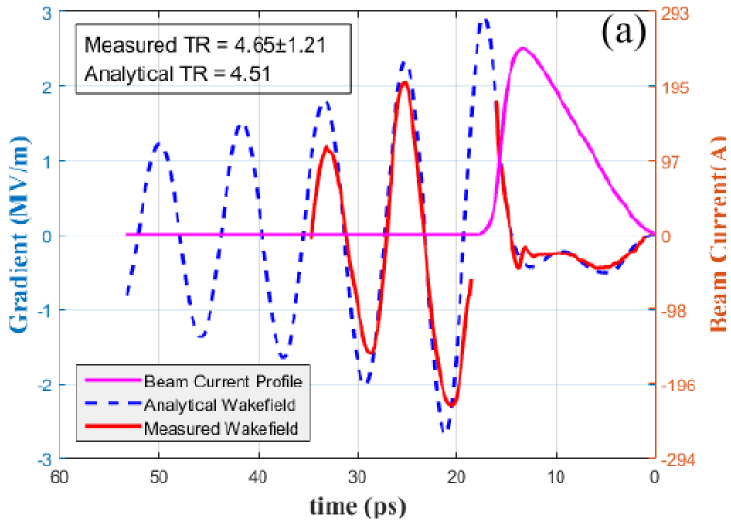
Experiment Demonstration

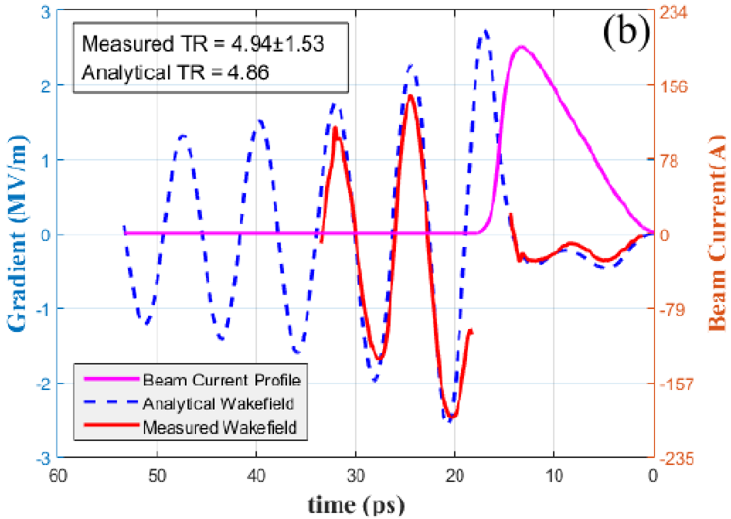


Reconstructed longitudinal phase space and measured wakefield: (a) Longitudinal phase space full envelope. (b)Average profile in LPS. (c) Average profiles error bar in LPS. (d) Measured energy gain induced by wakefield.

- When the gap size is 2.5 mm, the total charge of drive bunch travelling through is 2.08nC, and the witness charge is 1.06nC.
- Figure (a) shows the single shot phase space profile of wakefield on and off.
- Figure (b) is average energy profile of LPS for both cases.
- Figure (c) shows the fluctuation between shot and shot.
- Figure (d) is the measured wakefield of drive bunch.

Experiment Demonstration





- Both short and long range wakefield are measured and compared with analytical result as shown in figure (a) and (b), whose gap size is 2.5 mm and 2.1 mm.
- The ideal wakefield can be derived from the following equation:

$$W(t) = \int_0^t \sum_{m=1}^{80} \sum_{n=1}^{10} I(\tau) G_{mn}(t-\tau) d\tau$$

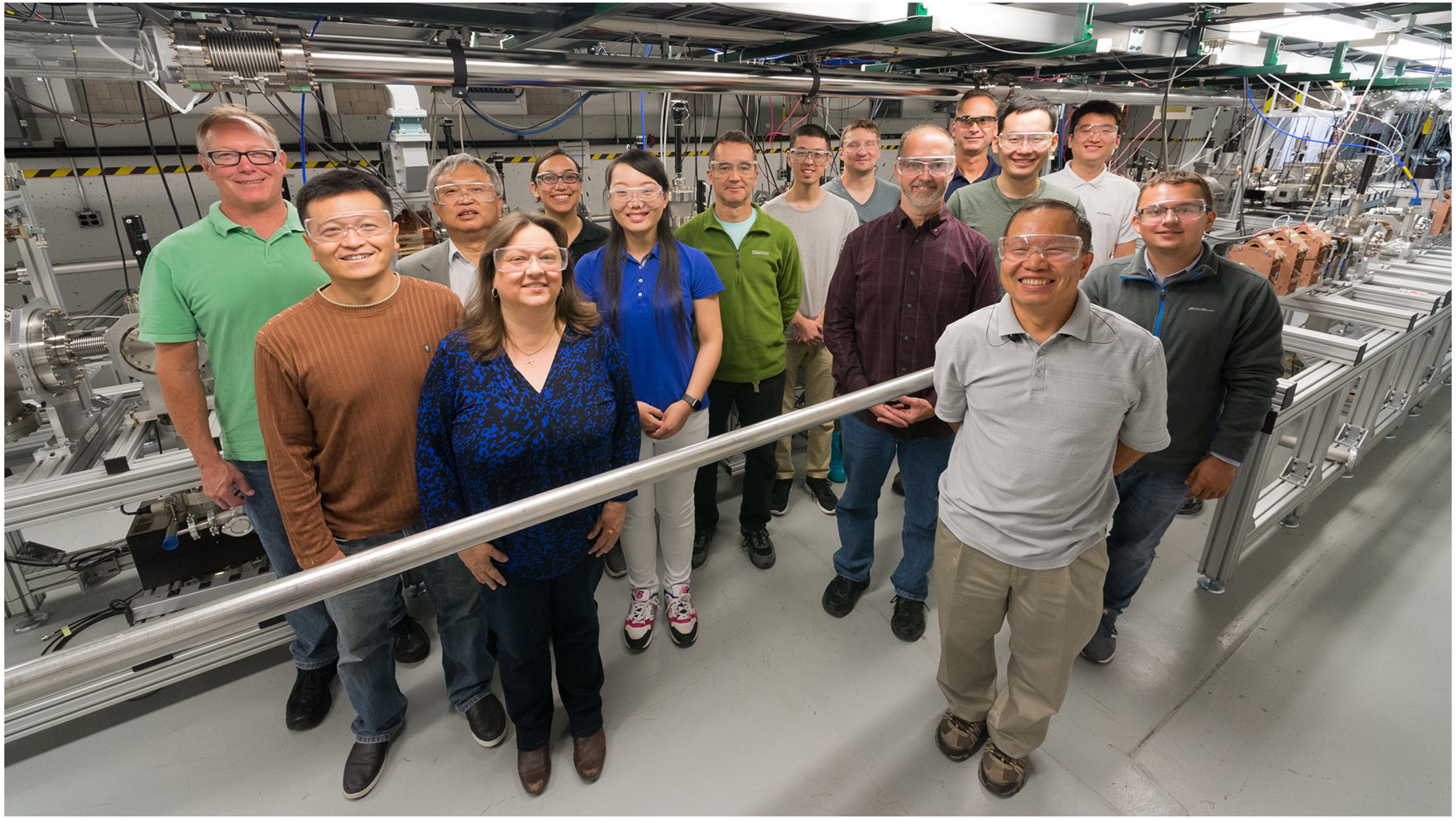
- The Transformer ratio value is compared with analytical one, which shows a good agreement.
- The measured wakefield strength is slightly lower than analytical value, reasons:
  - The beam size at x direction (width direction) is non-negligible.
  - The strength of wake function derived from dielectric fill wave guide model is overestimated than the realistic slab model.

Outline

- Introduction and Motivation
- Theory of Single-Shot Wakefield Mapping Method
- Beam Dynamic Simulation
- Experiment Demonstration
- Conclusion

Conclusion

- Single-shot wakefield measurement system consists of two main elements:
  - Long witness bunch (longer than the region of interest)
  - Longitudinal phase space mapping system
- Single-shot wakefield measurement system features:
  - No need for dedicated scanning tool
  - Capability of measuring both short and long range wakefield
  - Capability of measuring THz wakefield
- Both simulation and experiment demonstrate that it can measure the wakefield precisely.
- Single-shot wakefield measurement system may be a general tool for wakefield measurement, especially for Transformer Ratio measurement.



Thank you for your attention