MOTIVATION

> LINEAR ACCELERATOR

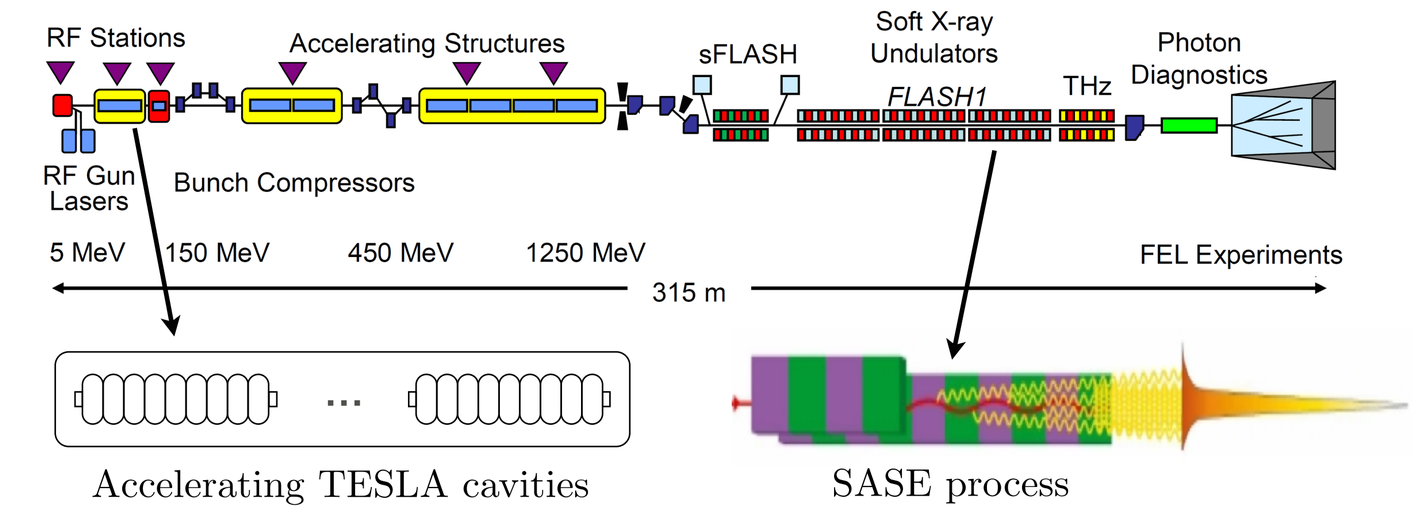
- Photo cathode RF gun
- SRF cavities
- 2 stage bunch compression

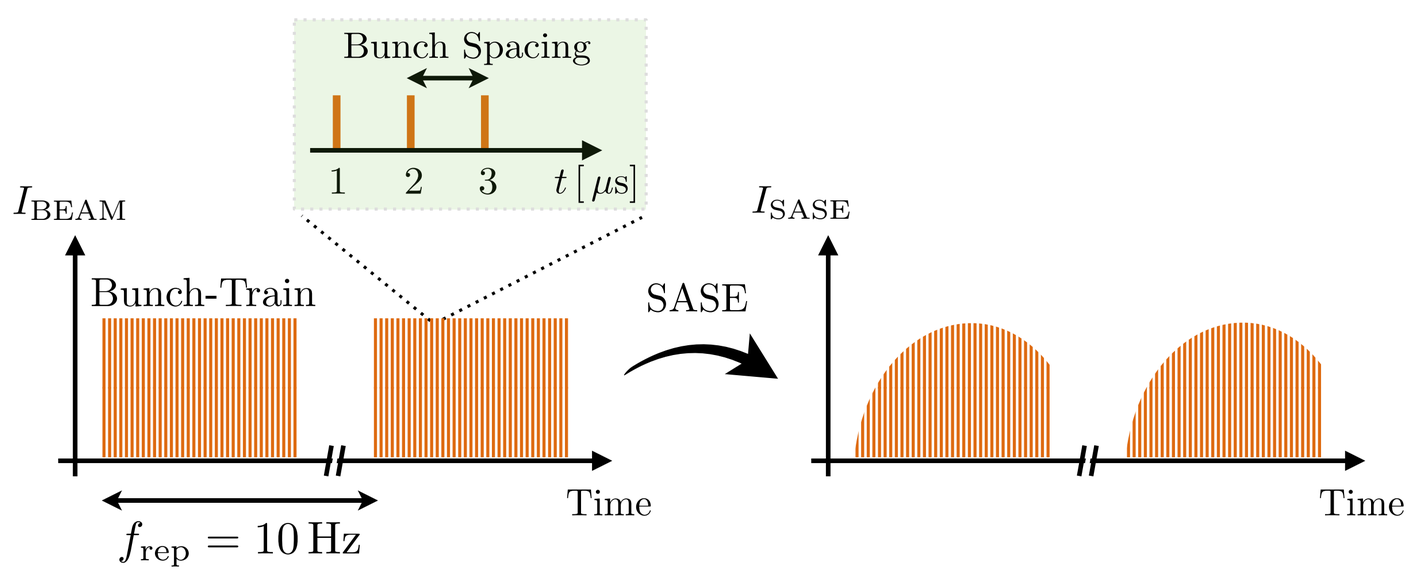
> SASE PROCESS

- Fixed gap undulator
- High brilliance photon pulses

> MULTI-BUNCH OPERATION

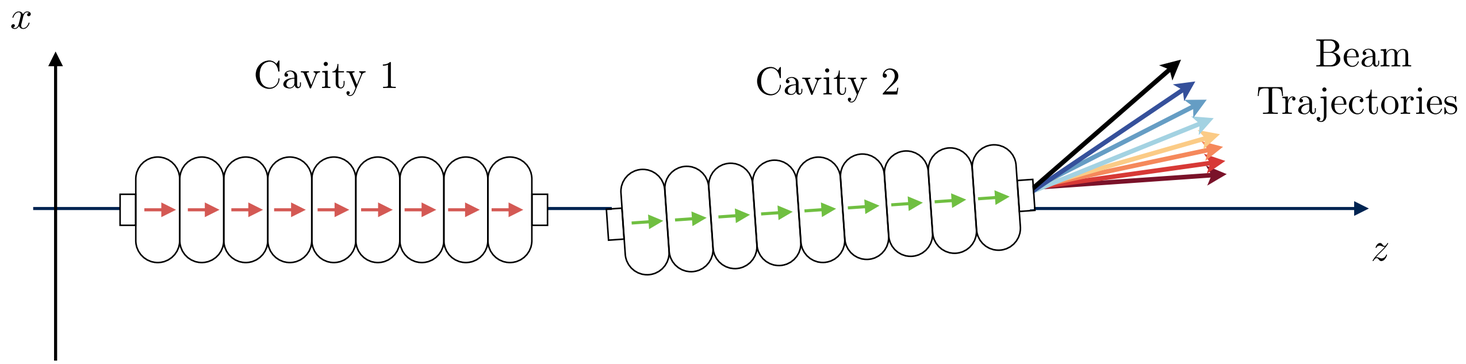
- Pulsed RF
- High duty cycle
- Long bunch-trains
- 10^3 photon pulses per second

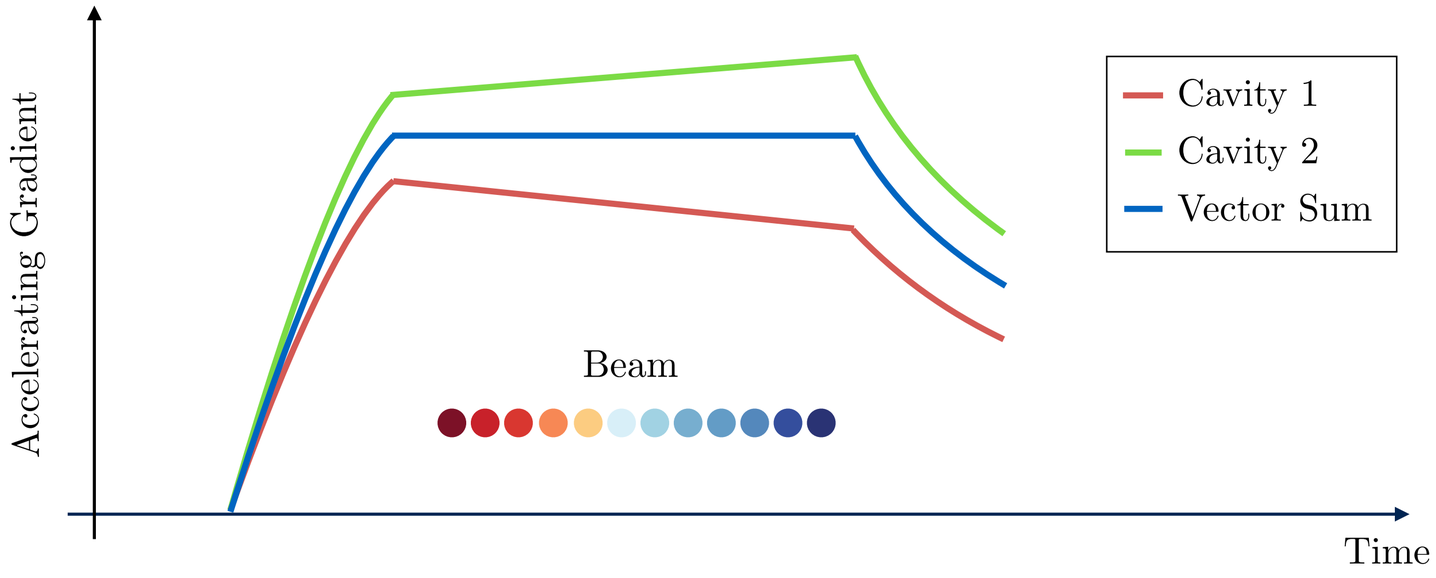




MOTIVATION

- TESLA CAVITY
- PULSED OPERATION
- GRADIENT SPREAD
- VECTOR SUM RF CONTROL
- GRADIENT SLOPES
  - Quality factor setup
  - Beam loading
  - Lorentz force detuning
- MISALIGNMENTS
- TRAJECTORY VARIATIONS
  - Off-axis fields
  - Coupler kicks





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- GRADIENT SPREAD
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  - Quality factor setup
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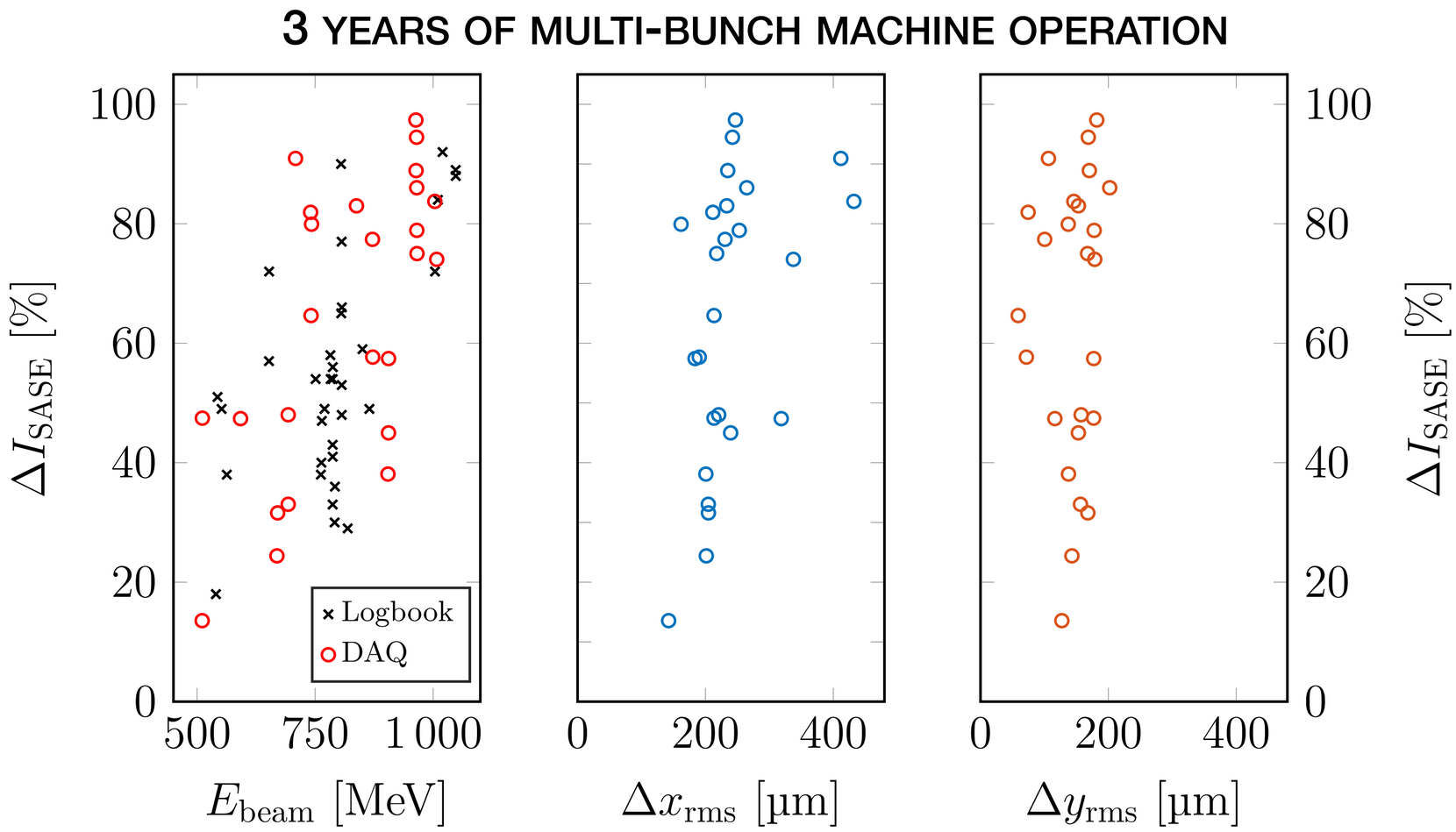
- MISALIGNMENTS
- TRAJECTORY VARIATIONS
- SASE VARIATIONS
  - Reduce performance
  - Depend on hor. trajectory variation



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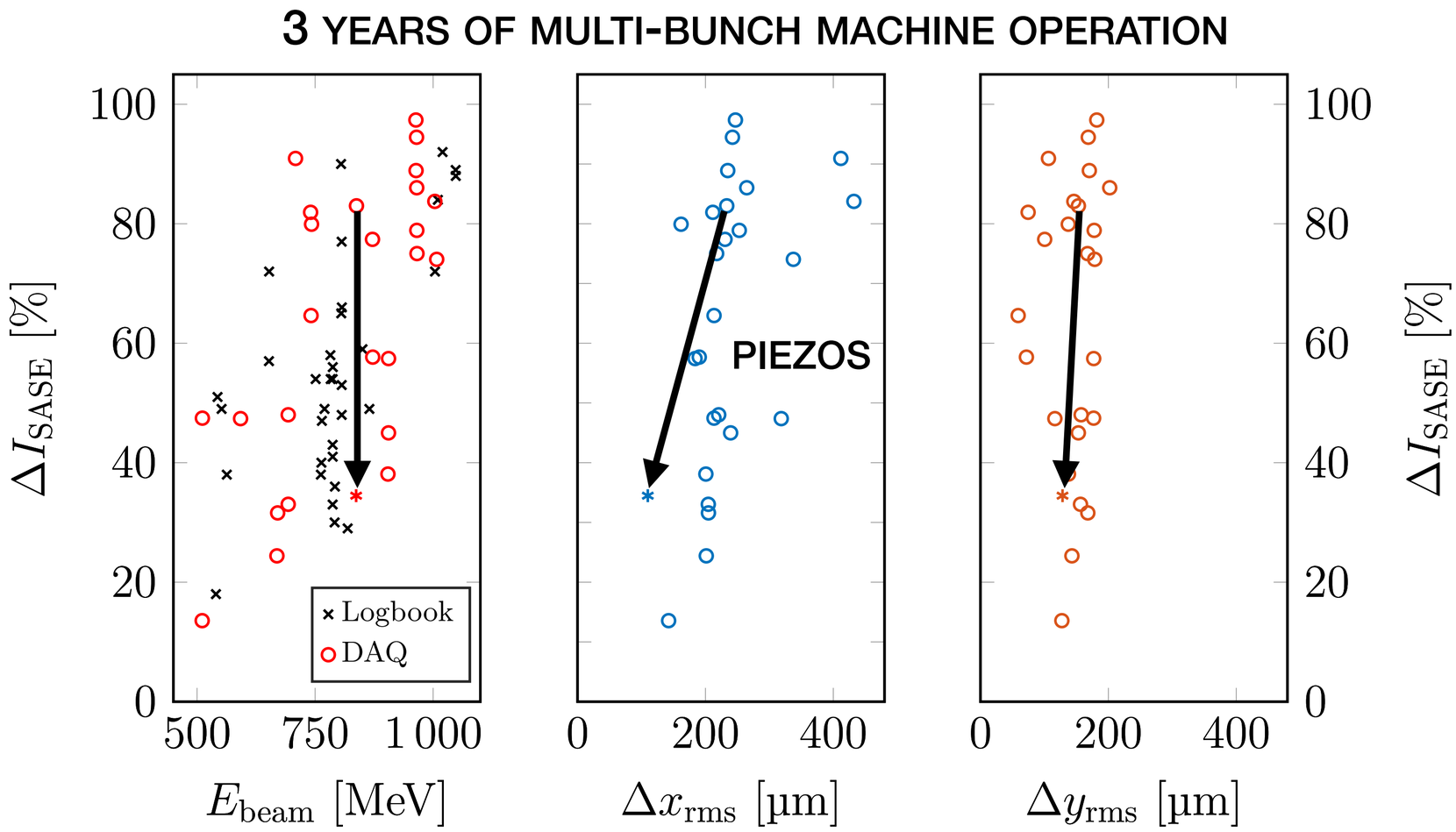


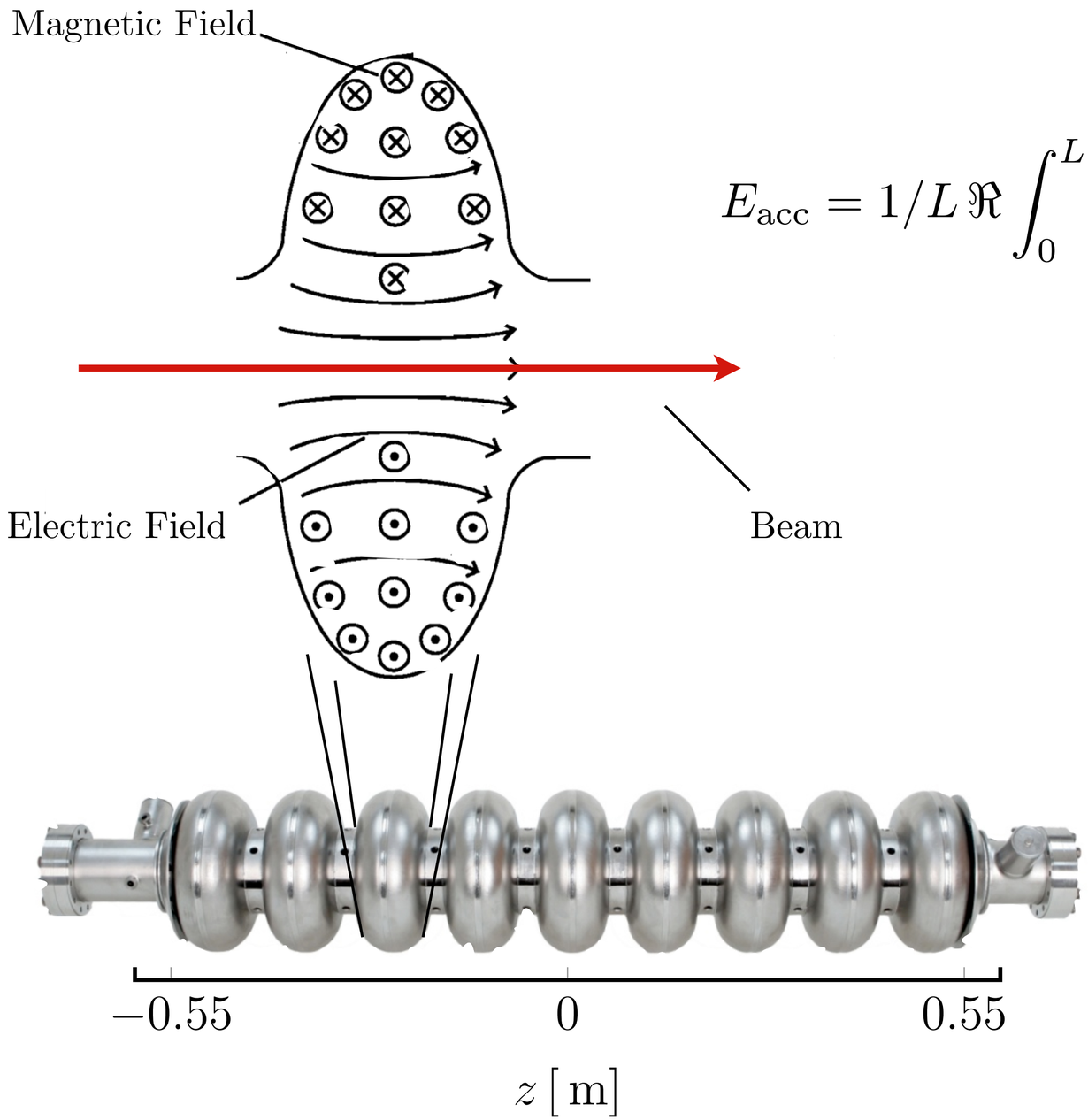
Outline

- Motivation
- Discrete coupler kicks
- Coupler kick studies

DISCRETE COUPLER KICKS

> TESLA CAVITY

- Superconducting
- $T_c/T = 4.6$
- 9 cell standing wave
- $f_\pi = 1.3\,\mathrm{GHz}$
- $Q_0 \approx 10^{10}$



$$E_{\mathrm{acc}} = 1/L\,\Re \int_0^L E_z(z,t)\,e^{i\omega z/c} dz$$

DISCRETE COUPLER KICKS

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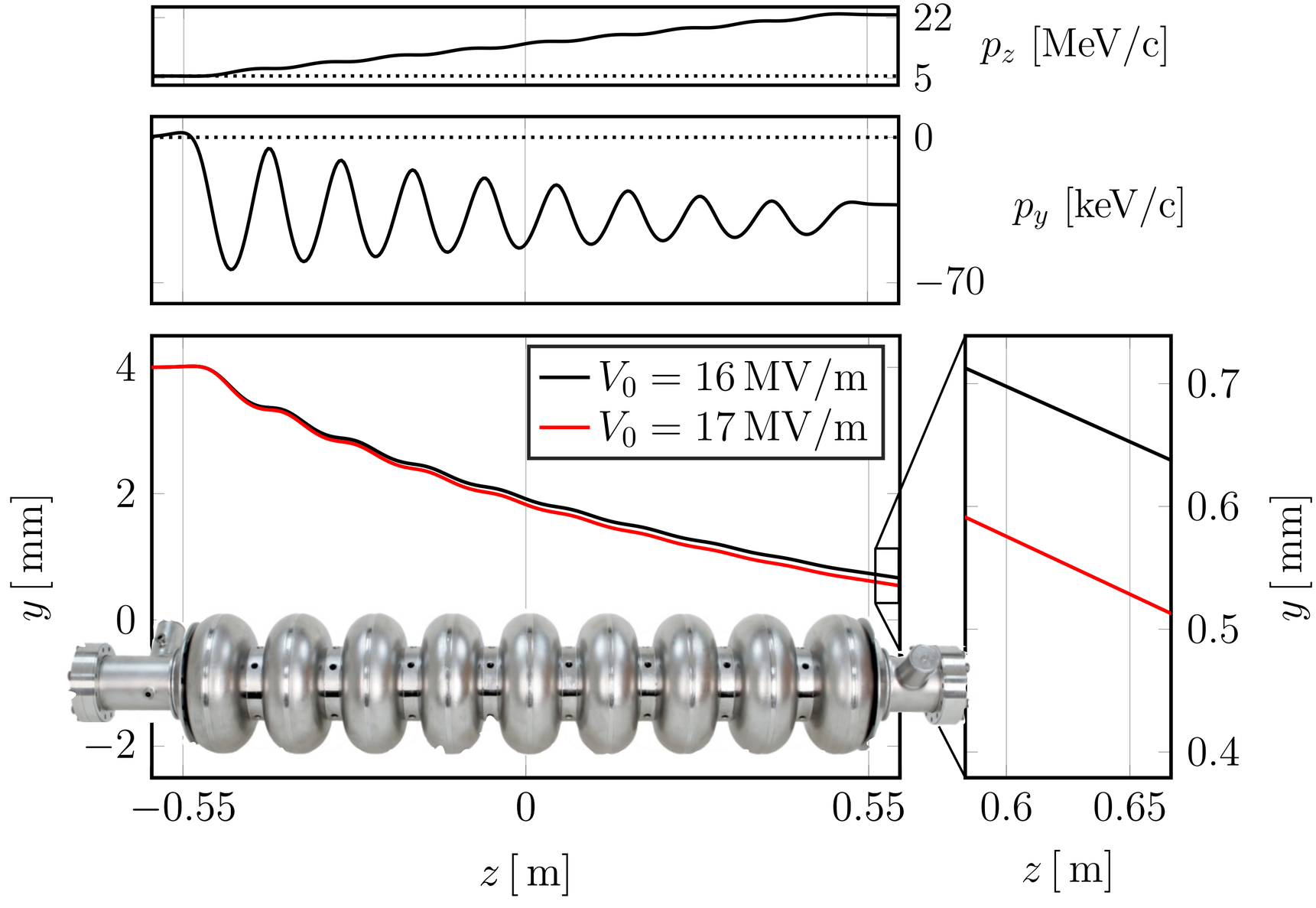

DISCRETE COUPLER KICKS

> TESLA CAVITY

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- $T_c/T = 4.6$
- 9 cell standing wave
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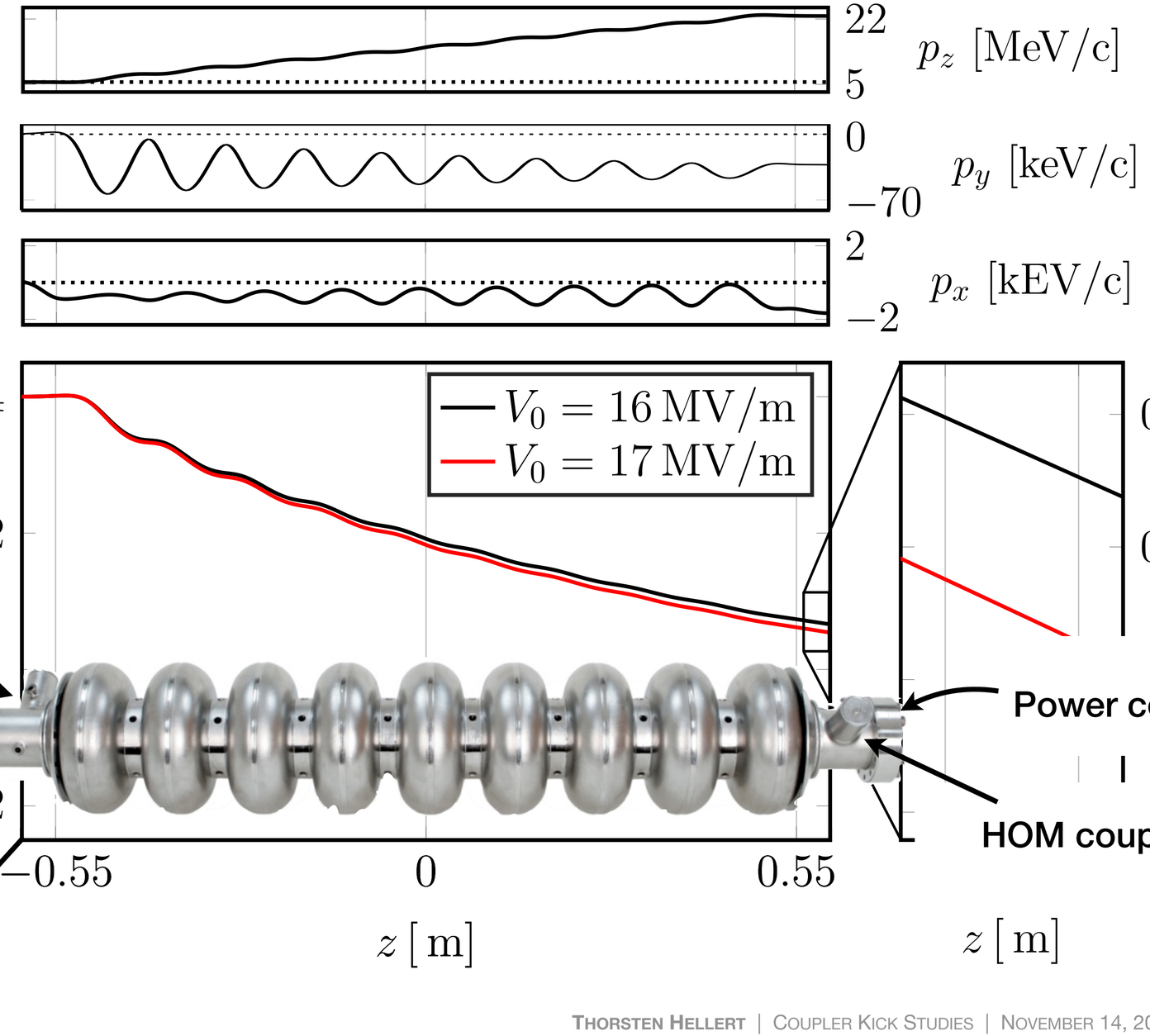
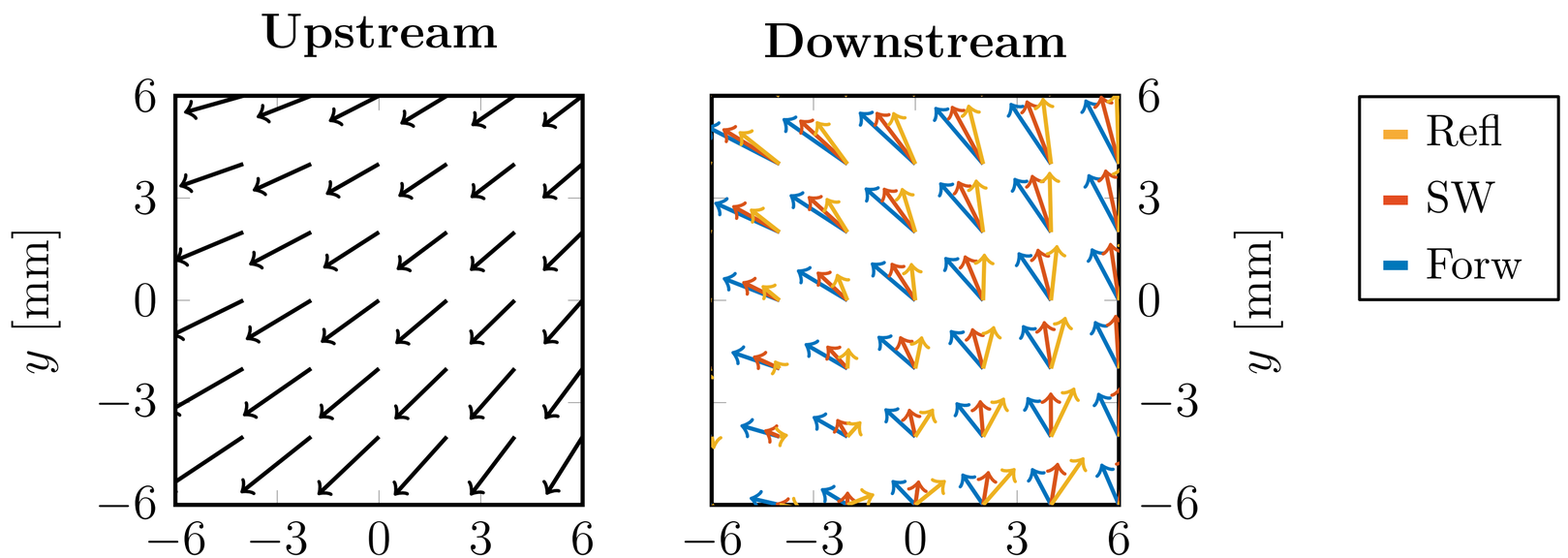
- Ax. sym. RF focusing
- 2 HOM couplers
- Power coupler



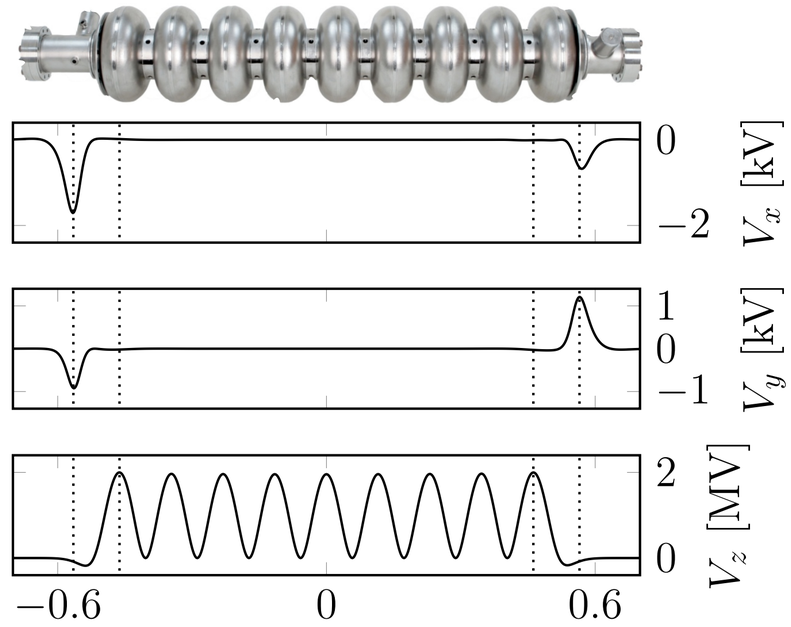
DISCRETE COUPLER KICKS

- **TESLA CAVITY**
  - Superconducting
  - $T_c/T = 4.6$
  - 9 cell standing wave
  - $f_\pi = 1.3\,\mathrm{GHz}$
  - $Q_0 \approx 10^{10}$
  - Ax. sym. RF focusing
  - 2 HOM couplers
  - Power coupler
  - Coupler kicks (Detuning)



> DISCRETE COULER KICKS

- **Int. trans. field strength:** $\mathbf{V}_\perp(x,y) = \int dz \left[\vec{E}_\perp(\vec{r}) + c\,\vec{e}_z \times \vec{B}(\vec{r})\right] e^{i\frac{\omega z}{c}}$
- **From couplers:** $\mathbf{V}_\mathrm{c}(x,y) = \mathbf{V}_\perp(x,y) - \mathbf{V}_\mathrm{RZ}(r)$
- **Normalized kick factor:** $\tilde{\mathbf{V}}(x,y) = \dfrac{\mathbf{V}_c(x,y)}{\int dz\, \vec{e}_z \cdot \vec{E}(0,0,z) e^{i\frac{\omega z}{c}}}$
- **Coupler kick:** $\vec{k}(x,y) = \dfrac{e\,V_0}{E_0} \Re\left\{\tilde{\mathbf{V}}(x,y) \cdot e^{i\phi}\right\}$

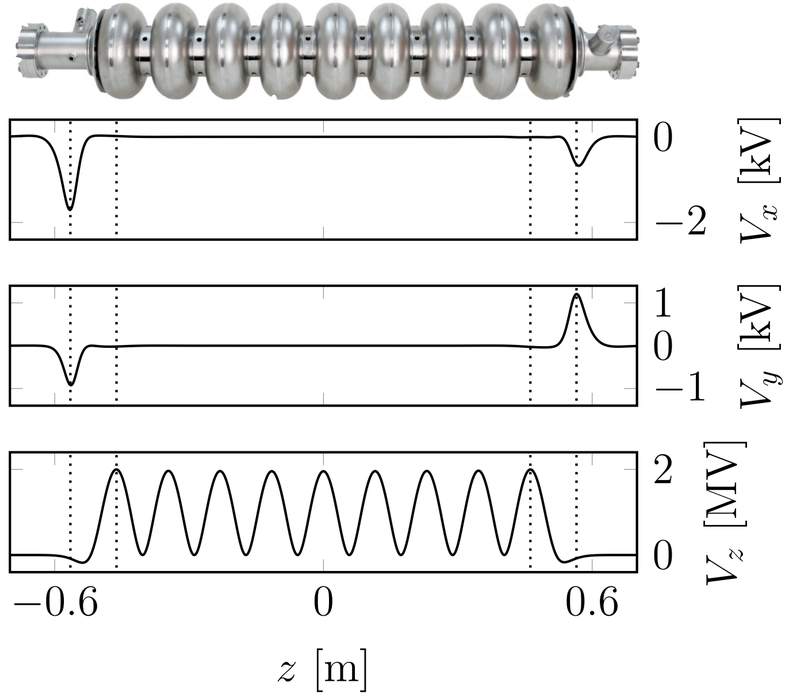


> FIELD CALCULATION

- **3D field map (decay):** $\vec{E}_b(\vec{r},t) = \vec{E}_b^{cos}(\vec{r})\cos(\omega t) + \vec{E}_b^{sin}(\vec{r})\sin(\omega t)$
- **General case:** $\vec{E}(\vec{r},t) = \Re\left[V_0/V_n\, e^{i(\omega t+\phi)} \cdot \left(\vec{E}_b^{cos}(\vec{r}) + i\,\mathbf{\Gamma}\cdot\vec{E}_b^{sin}(\vec{r})\right)\right]$
- **Reflection:** $\mathbf{\Gamma} = (A_b e^{i\phi_b} - A_f e^{i\phi_f})/(A_b e^{i\phi_b} + A_f e^{i\phi_f})$

> DISCRETE COUPLER KICKS

- **Coupler kick:** $\vec{k}(x,y) = \frac{e\,V_0}{E_0} \Re\left\{\tilde{\mathbf{V}}(x,y)\cdot e^{i\phi}\right\}$
- **Normalized kick factor:** $\tilde{\mathbf{V}}(x,y) = \frac{1}{2}\,\tilde{\mathbf{V}}^{\mathrm{SW}}(x,y) + \frac{\mathbf{\Gamma}}{2}\,\tilde{\mathbf{V}}^{\mathrm{R}}(x,y)$
- **Standing wave:** $\tilde{\mathbf{V}}^{\mathrm{SW}} = \tilde{\mathbf{V}}^{f} + \tilde{\mathbf{V}}^{b}$
- **Reflection dependent:** $\tilde{\mathbf{V}}^{\mathrm{R}} = \tilde{\mathbf{V}}^{f} - \tilde{\mathbf{V}}^{b}$
- **Linearization:** $\tilde{\mathbf{V}}(x,y) \approx \begin{pmatrix} V_{0x} \\ V_{0y} \end{pmatrix} + \begin{pmatrix} V_{xx} & V_{xy} \\ V_{xy} & -V_{xx} \end{pmatrix} \cdot \begin{pmatrix} x \\ y \end{pmatrix}$
- **Coupler kick coefficients:** $[V_{0x}, V_{0y}, V_{xx}, V_{xy}]$



> COUPLER KICK COEFFICIENTS

- $\vec{k}(x,y) = \frac{e\,V_0}{E_0}\Re\left\{\tilde{\mathbf{V}}(x,y)\cdot e^{i\phi}\right\}$
- $\tilde{\mathbf{V}}(x,y) = \frac{1}{2}\,\tilde{\mathbf{V}}^{\mathrm{SW}}(x,y) + \frac{\mathbf{\Gamma}}{2}\,\tilde{\mathbf{V}}^{\mathrm{R}}(x,y)$
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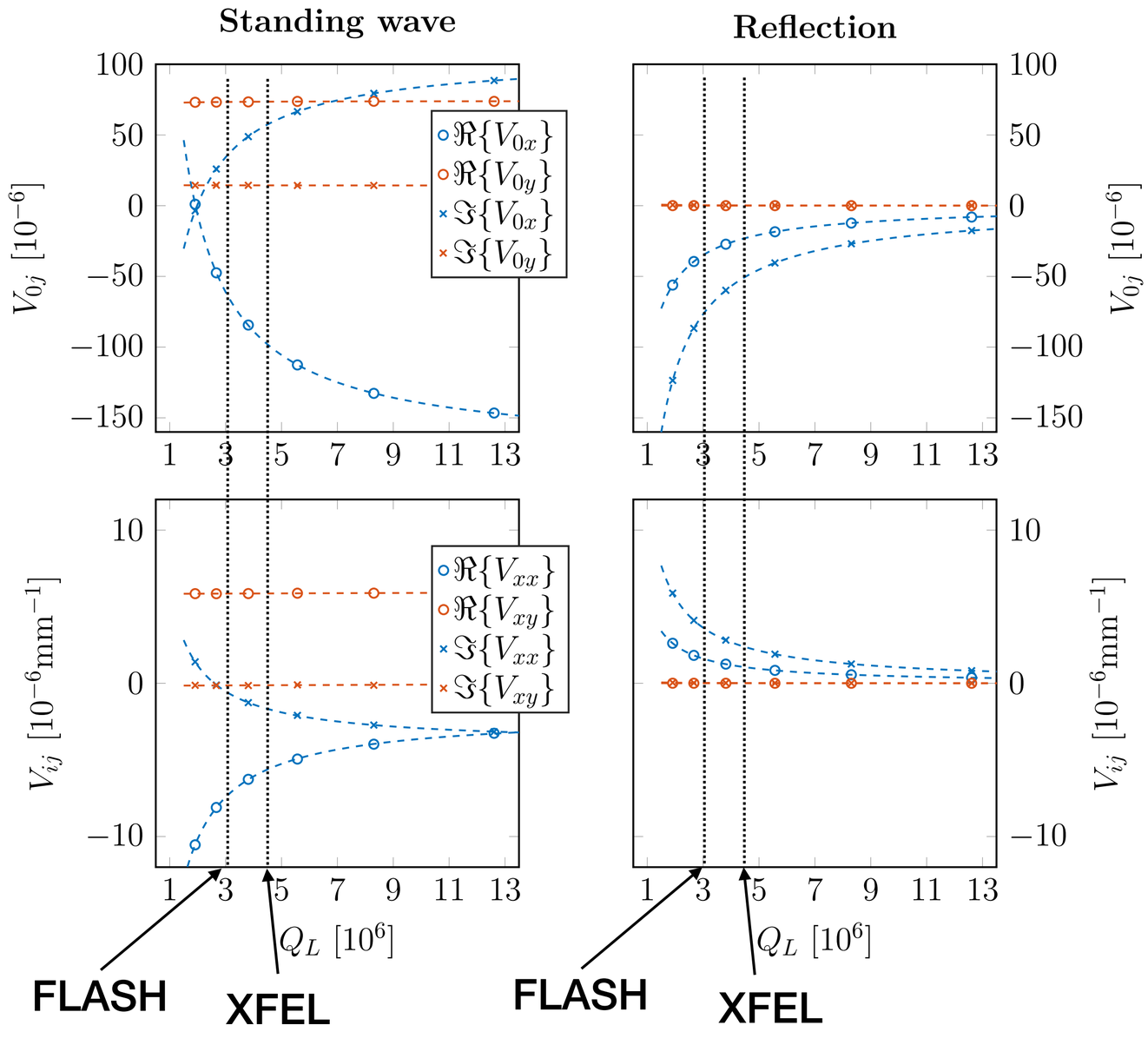
- $[V_{0x}, V_{0y}, V_{xx}, V_{xy}]$
- **Field maps available for different FPC-antenna positions: $Q_L = [2 \ldots 13] \times 10^6$**



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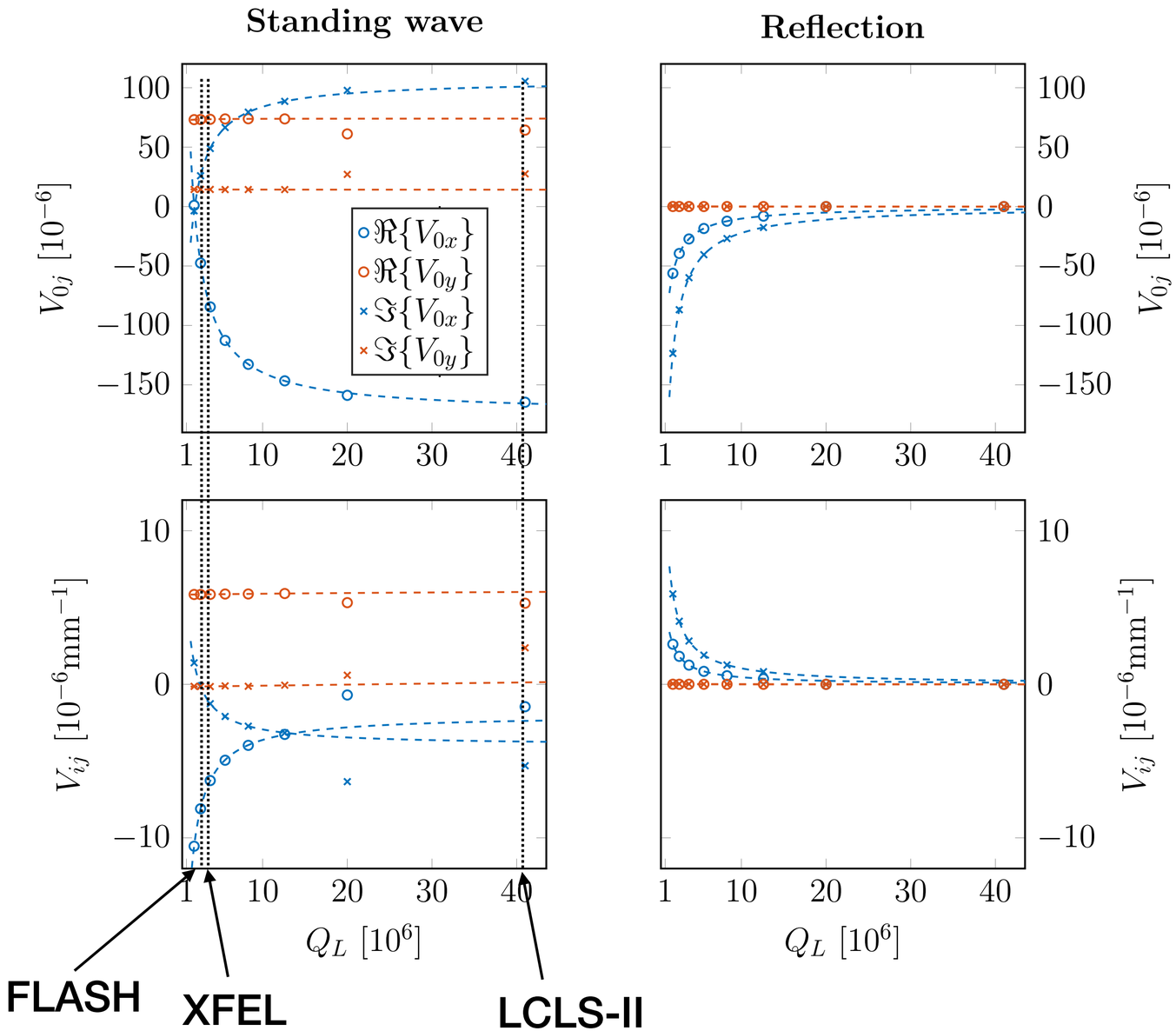
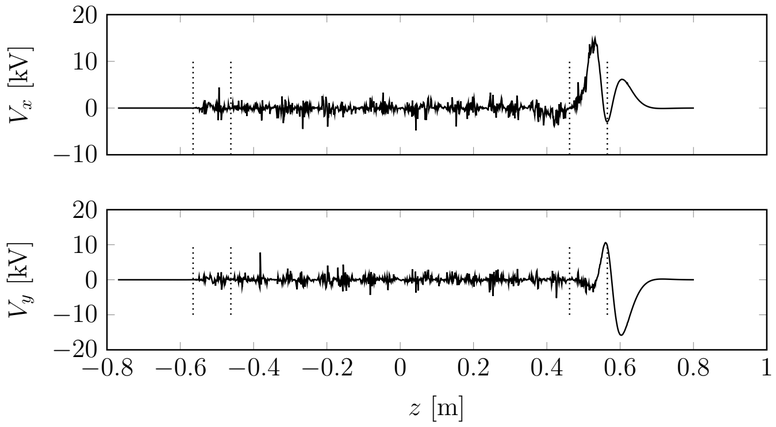
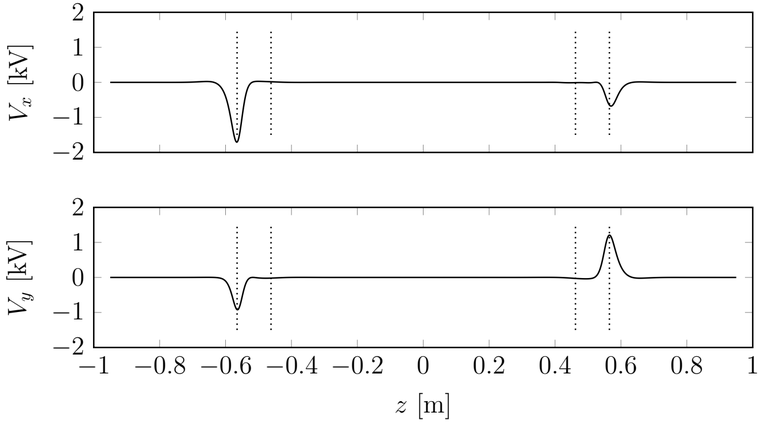


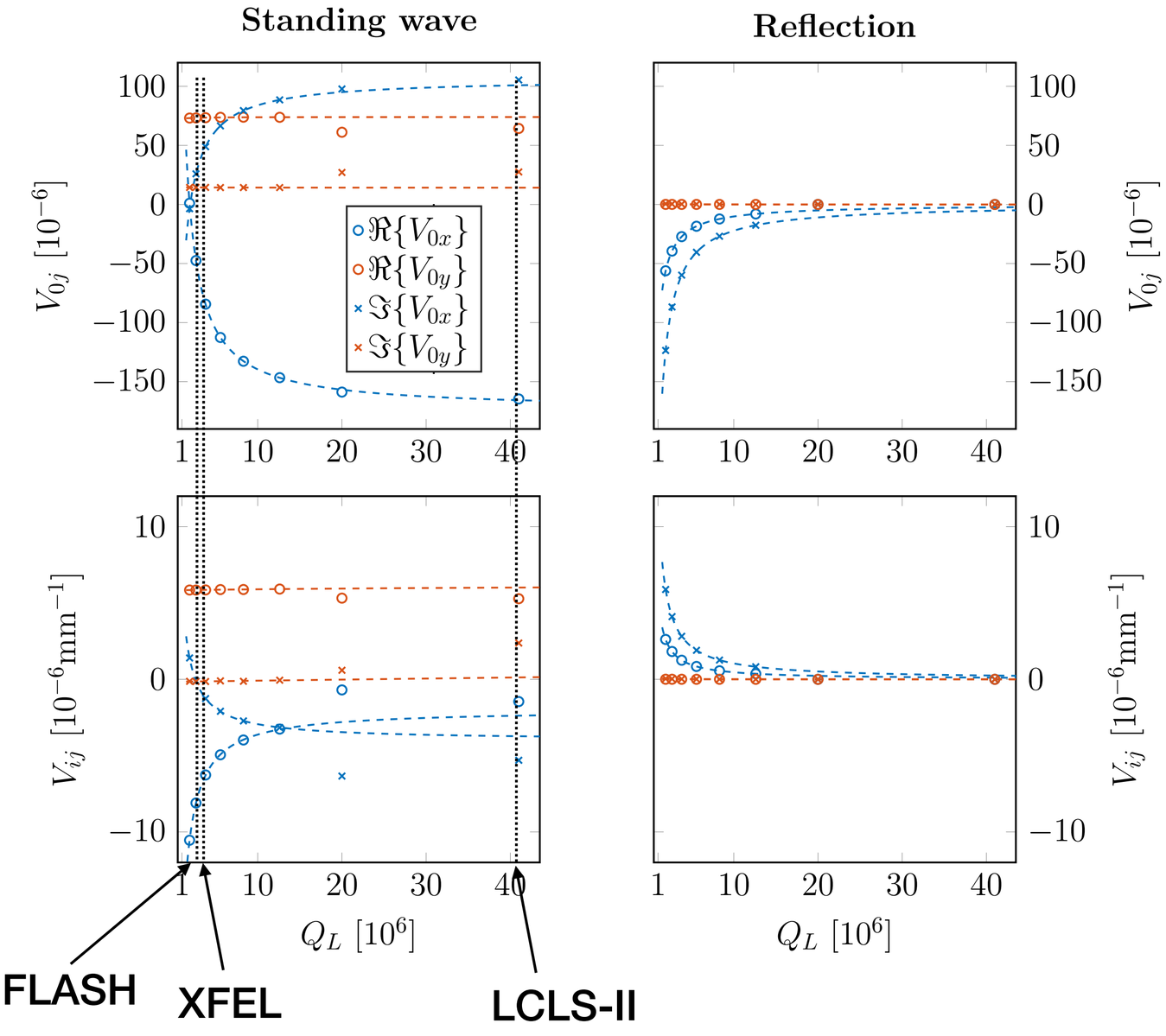
> FIELD MAPS

- **LCLS-II field map (SW):**



- **TEMF field map (TW):**



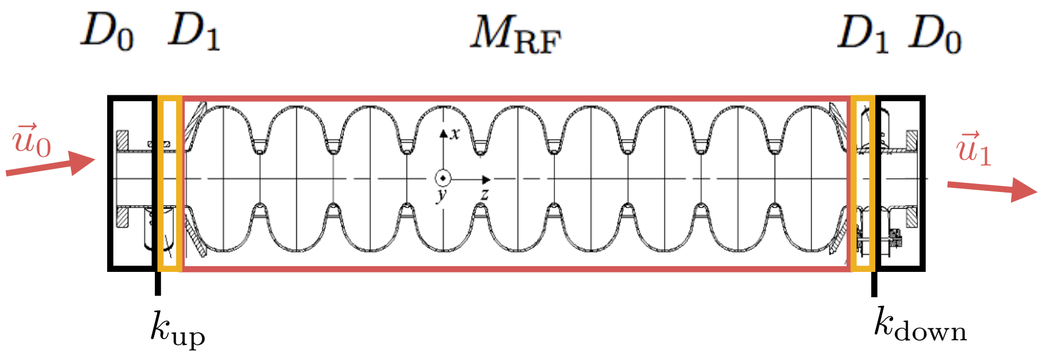


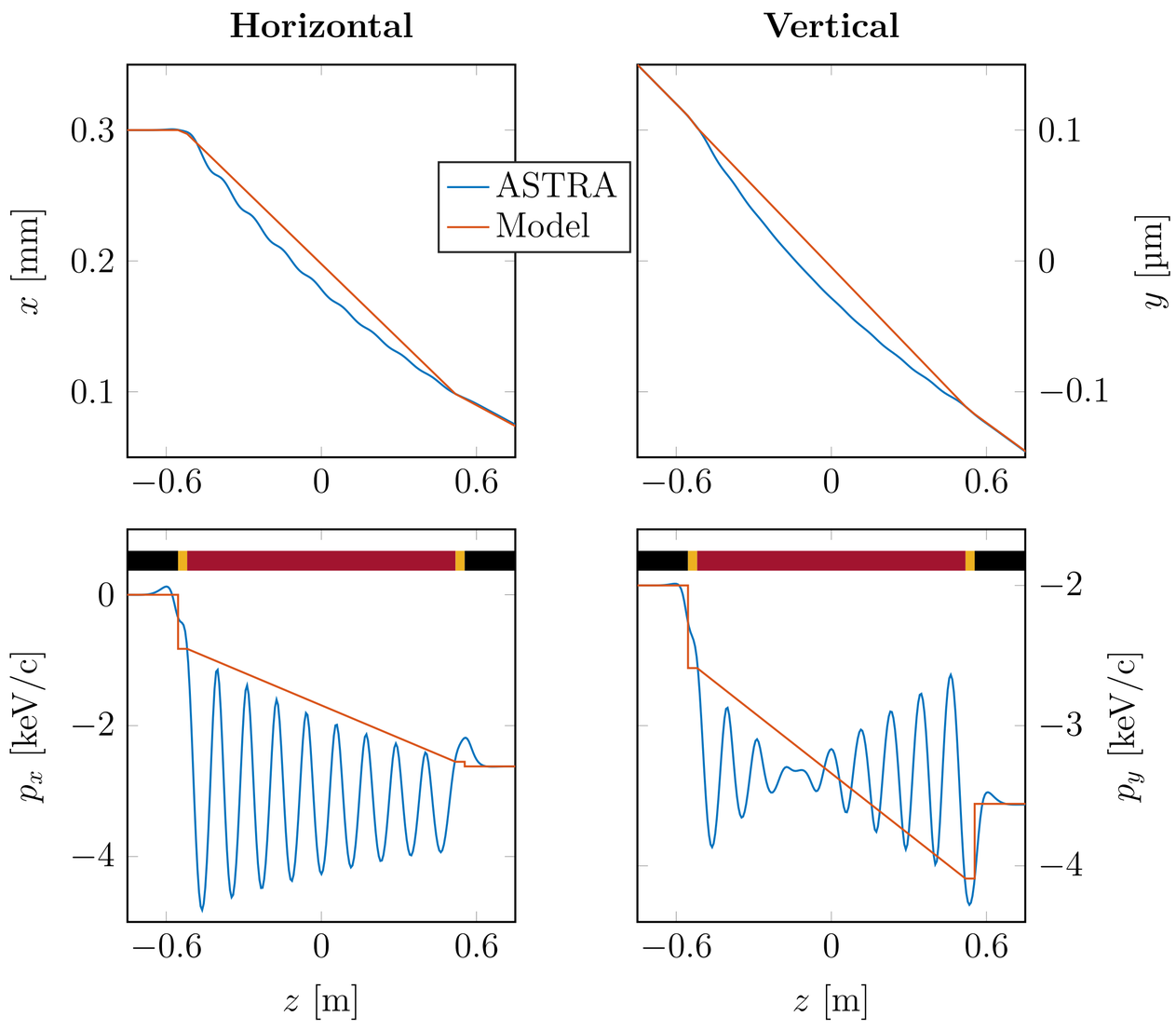
Outline

- Motivation
- Discrete coupler kicks
- **Coupler kick studies**

> DISCRETE COULER KICK MODEL

- $\vec{k}(x,y) = \dfrac{e\,V_0}{E_0}\Re\left\{\tilde{\mathbf{V}}(x,y)\cdot e^{i\phi}\right\}$
- $\tilde{\mathbf{V}}(x,y) \approx \begin{pmatrix} V_{0x} \\ V_{0y} \end{pmatrix} + \begin{pmatrix} V_{xx} & V_{xy} \\ V_{xy} & -V_{xx} \end{pmatrix} \cdot \begin{pmatrix} x \\ y \end{pmatrix}$
- $\vec{u}_1 = D_0 \cdot \vec{k}_{\text{down}} \left(D_1 \cdot M_{\text{RF}} \cdot D_1 \cdot \vec{k}_{\text{up}} \left(D_0 \cdot \vec{u}_0 \right) \right)$





> DISCRETE COULER KICK MODEL

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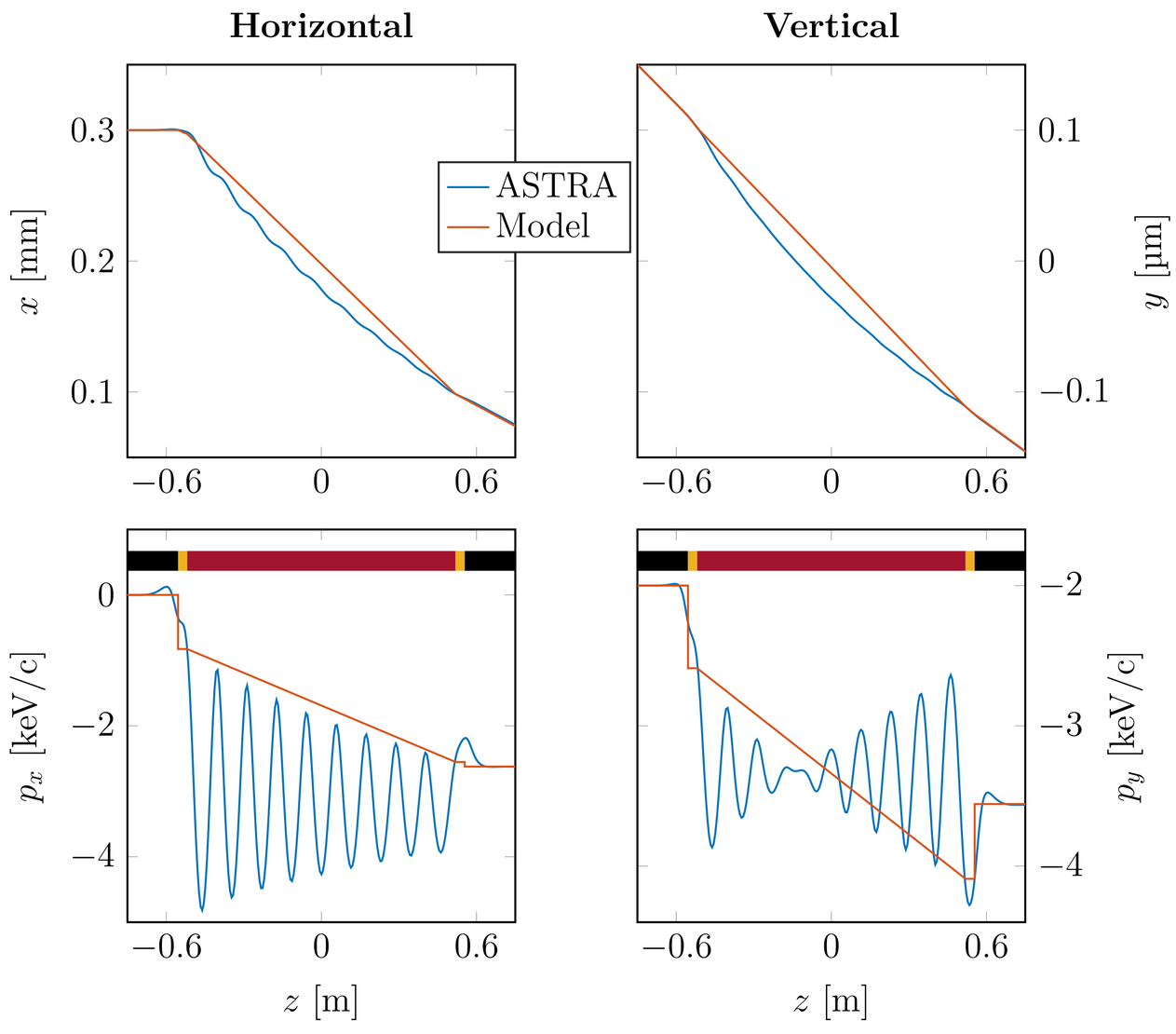
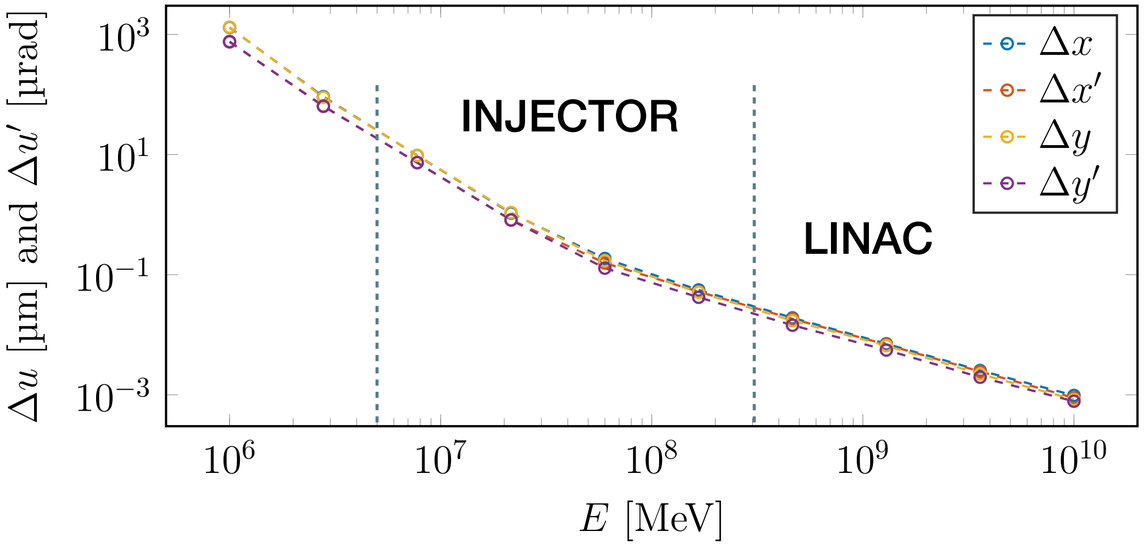
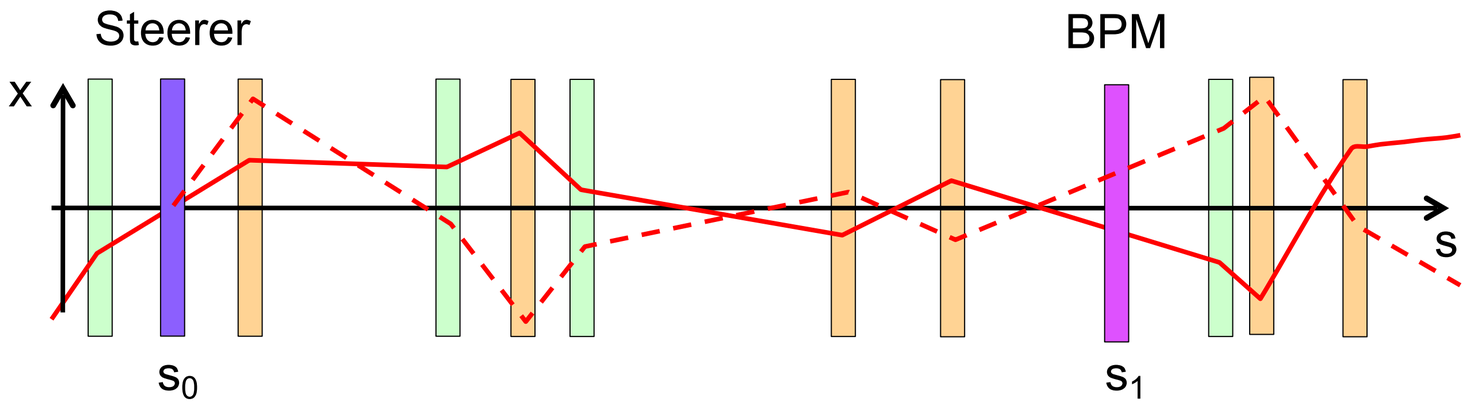




> TRAJECTORY RESPONSE

- Linear beam dynamics
- Change trajectory
- Measure R_{12}



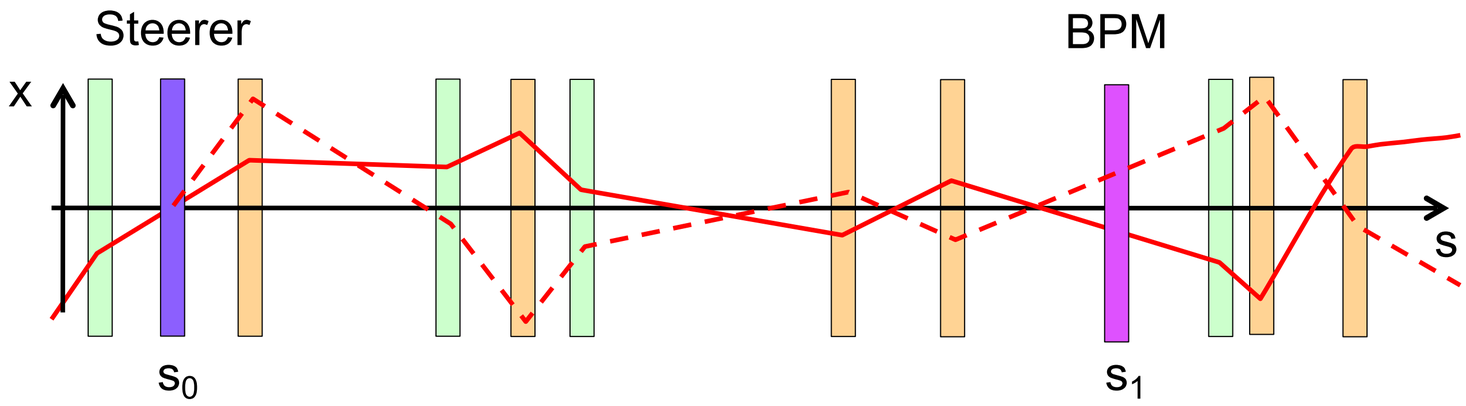
$$\begin{pmatrix} x \\ x' \end{pmatrix}_{s_1} = M_{\overline{s_1 s_0}} \begin{pmatrix} x \\ x' \end{pmatrix}_{s_0} = \begin{pmatrix} R_{11} & R_{12} \\ R_{21} & R_{22} \end{pmatrix} \begin{pmatrix} x \\ x' \end{pmatrix}_{s_0}$$

$$M_{\overline{s_1 s_0}} = M_{Drift} \cdot M_{QF} \cdot M_{Drift} \cdot M_{QD} \cdot M_{Drift} \cdot M_{QF} \quad \cdots$$

$$R_{12}^{s_1 s_0} = \frac{\Delta x(s_1)}{\Delta x'(s_0)}$$

> TRAJECTORY RESPONSE

- Linear beam dynamics
- Change trajectory
- Measure R_{12}
- Compare to optics model



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$$R_{12}^{s_1 s_0} = \frac{\Delta x(s_1)}{\Delta x'(s_0)}$$

TRAJECTORY RESPONSE MEASUREMENT

> DISCRETE COULER KICK MODEL

- $\vec{k}(x,y) = \frac{\Delta E}{E_0} \Re\left\{\tilde{\mathbf{V}}(x,y) \cdot \exp^{i\phi}\right\}$
- $\tilde{\mathbf{V}}(x,y) \approx \begin{pmatrix} V_{0x} \\ V_{0y} \end{pmatrix} + \begin{pmatrix} V_{xx} & V_{xy} \\ V_{xy} & -V_{xx} \end{pmatrix} \cdot \begin{pmatrix} x \\ y \end{pmatrix}$
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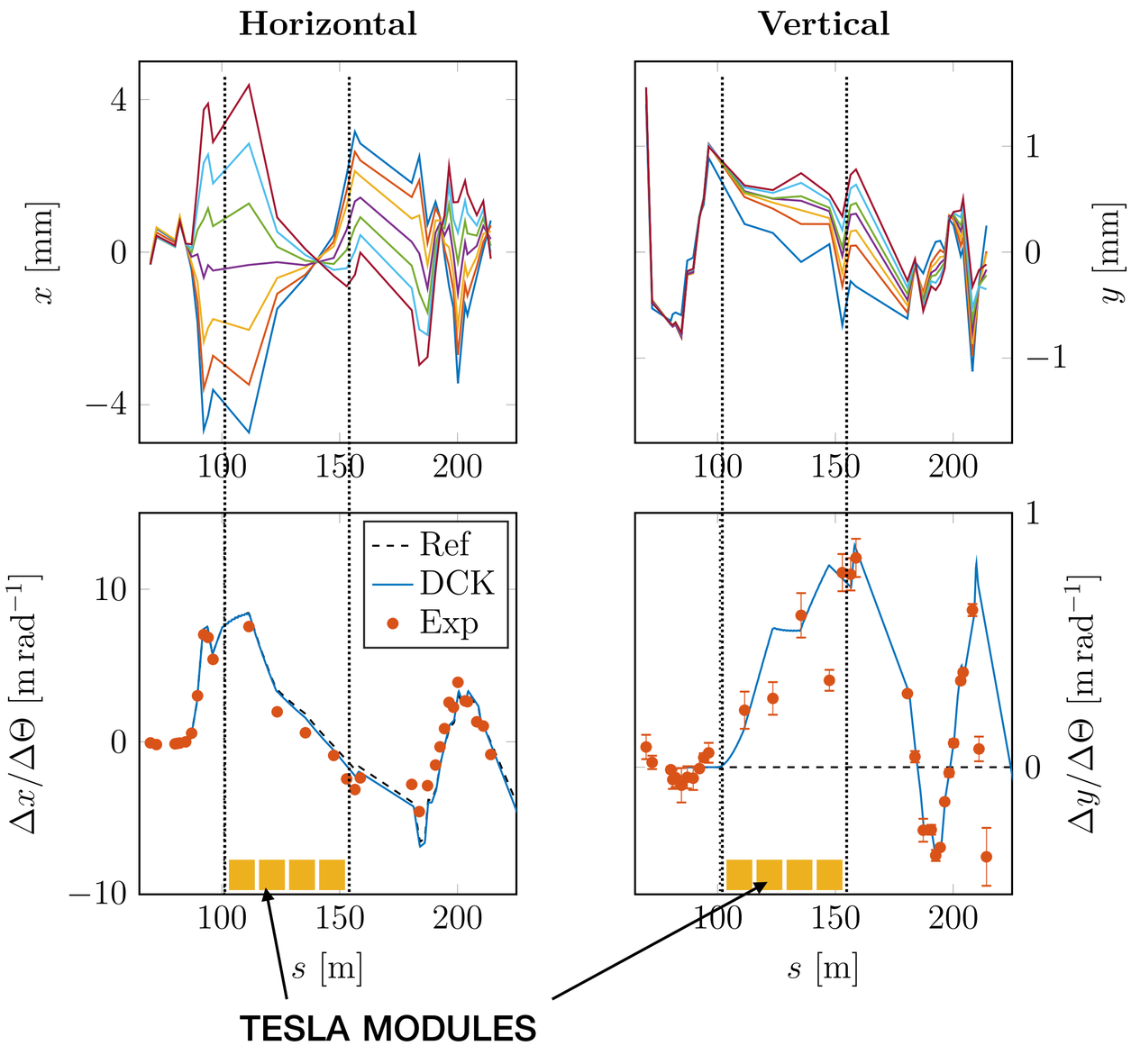
> TRAJECTORY RESPONSE MEASUREMENT

- First accelerating section at XFEL
- Transverse coupling in cavities
- Agrees with 1st order discrete coupler kick model

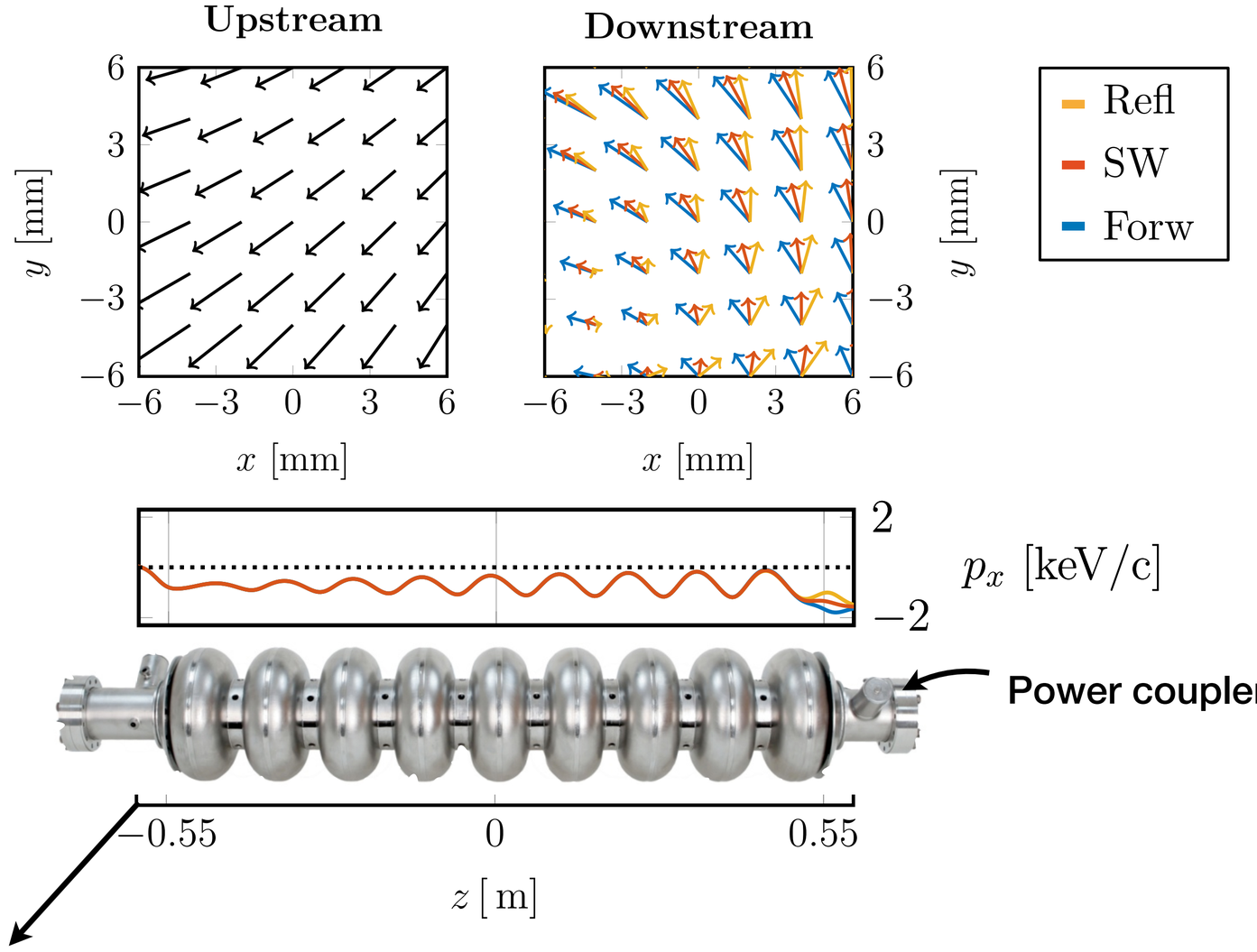
> *1ST ORDER MODEL REQUIRES HIGH PRECISION FIELD MAPS!*



COUPLER KICK STUDIES

> POWER COUPLER KICK

- Depends on cavity operation
- $\vec{k}(x,y) = \frac{e\,V_0}{E_0}\Re\left\{\tilde{\mathbf{V}}(x,y)\cdot e^{i\phi}\right\}$
- $\tilde{\mathbf{V}}(x,y) = \frac{1}{2}\,\tilde{\mathbf{V}}^{\mathrm{SW}}(x,y) + \frac{\mathbf{\Gamma}}{2}\,\tilde{\mathbf{V}}^{\mathrm{R}}(x,y)$



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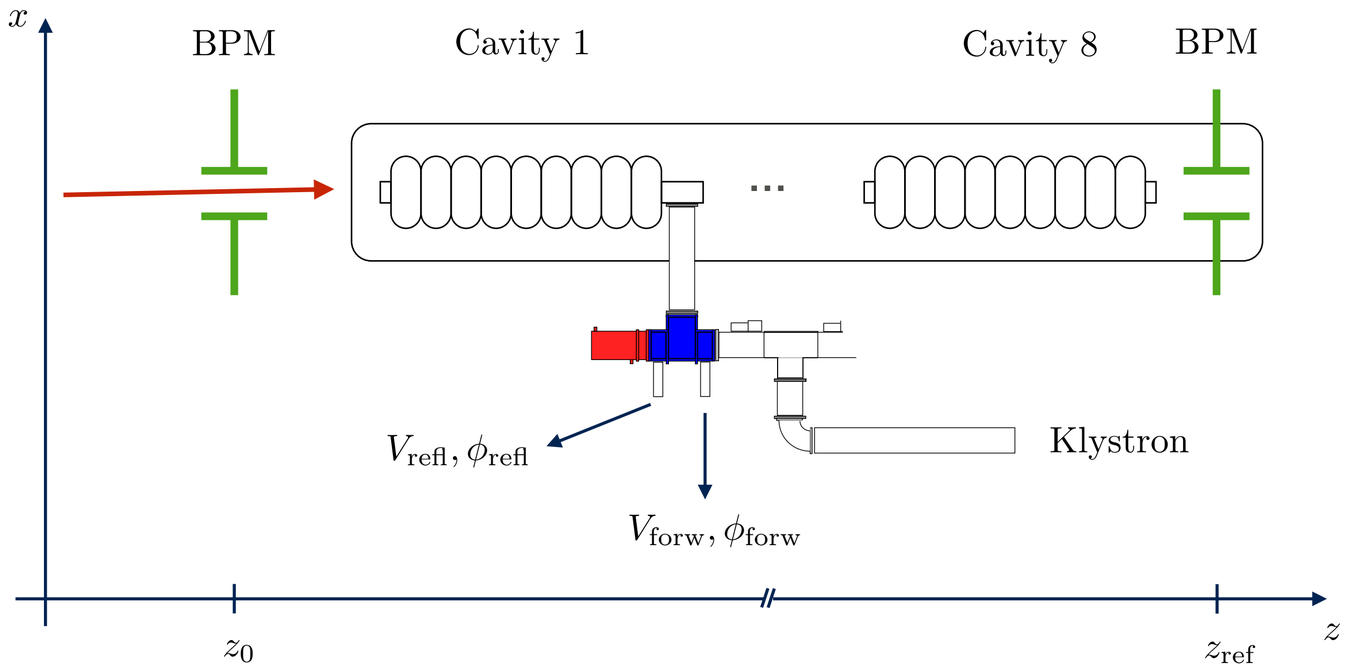
> FLASH (ACC6)

- Read BPM and RF data
- Modulate forward power



COUPLER KICK STUDIES

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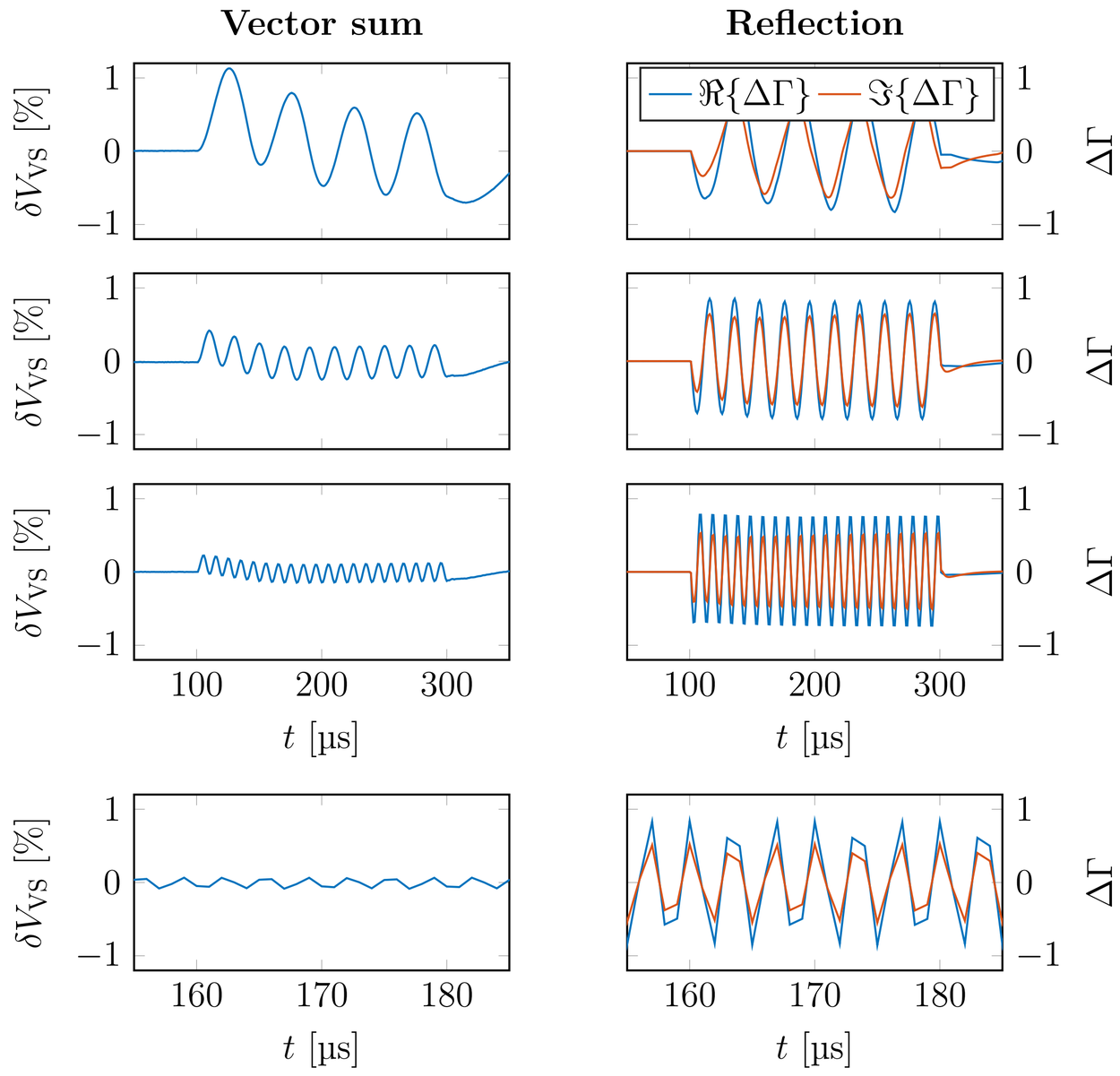
> FLASH (ACC6)

- Read BPM and RF data
- Modulate forward power

> FAST RF MODULATION

- Limited cavity bandwidth
- Cavity response decreases
- Response to reflection



COUPLER KICK STUDIES

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> FLASH (ACC6)

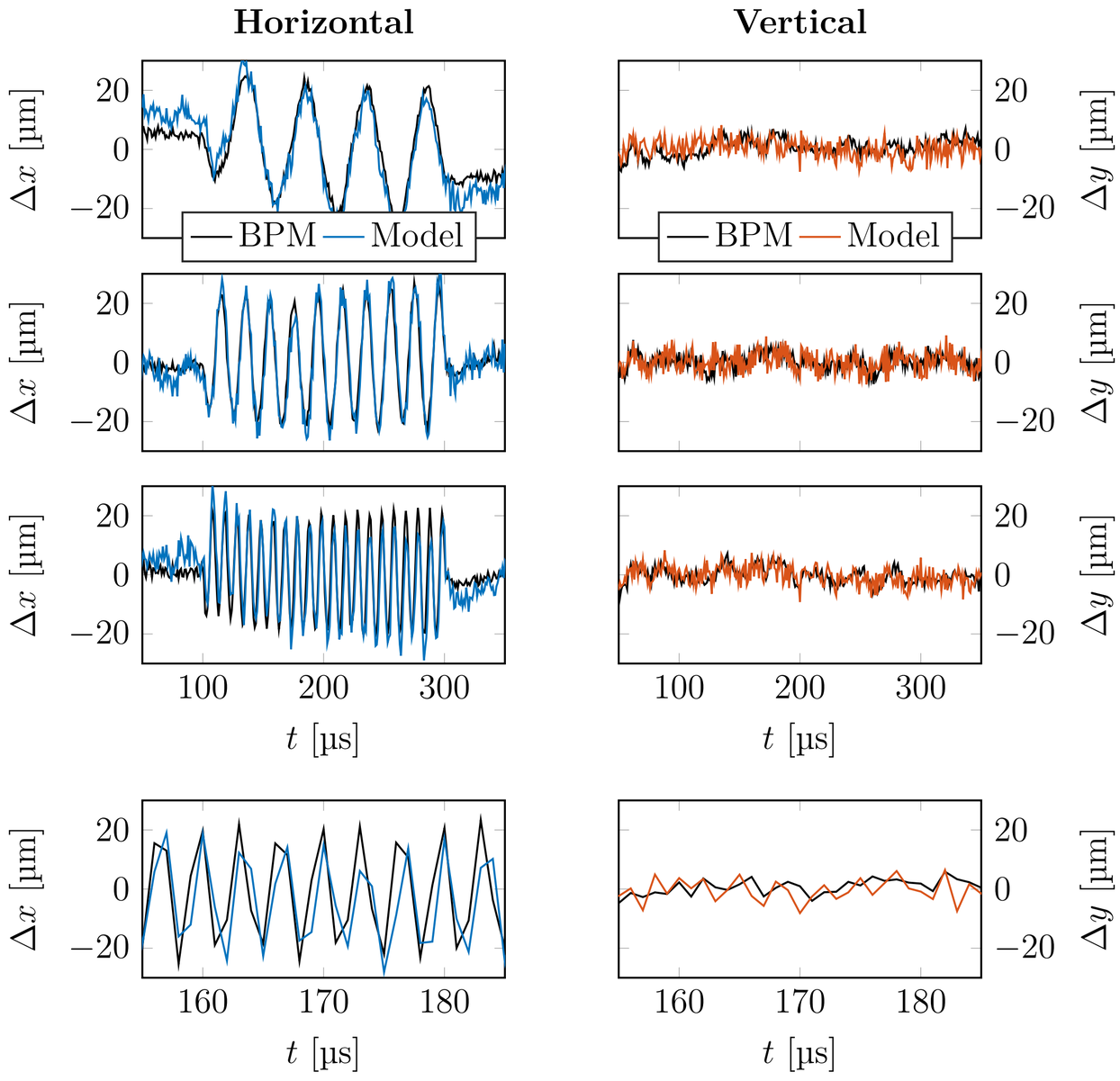
- Read BPM and RF data
- Modulate forward power

> FAST RF MODULATION

- Limited cavity bandwidth
- Cavity response decreases
- Response to reflection

> AGREES WITH TW COUPLER KICK MODEL

> *TW COUPLER KICK MODEL REQUIRES TW FIELD MAP!*



SUMMARY

> POWER COUPLER KICK

- Depends on cavity operation
- Affects transverse beam dynamics

> DISCRETE COUPLER KICK MODEL

- 1st order discrete coupler kick model
- Requires high precision TW field maps
- Depends on antenna penetration depth

> EXPERIMENTAL CONFIRMATION

- Transverse coupling
- Coupler kick variations

> FUTURE STUDIES(?)

- TW fieldmaps for LCLS-II
- Fieldmaps for 3.9 GHz cavity