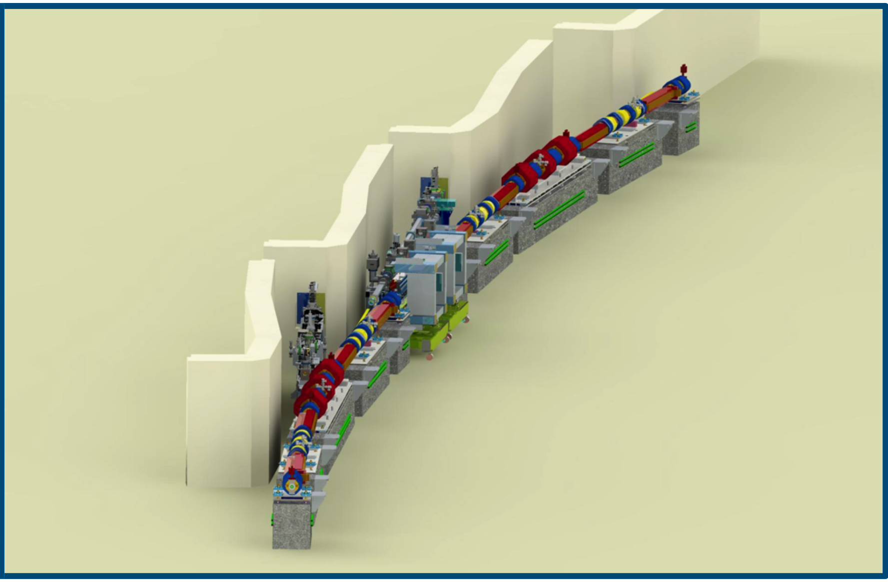
Physics considerations for APS-U vacuum design



Ryan Lindberg and Joe Calvey
Physicists
Accelerator Operations and Physics Group

Accelerator Systems Division Seminar
June 7, 2017

Acknowledgments

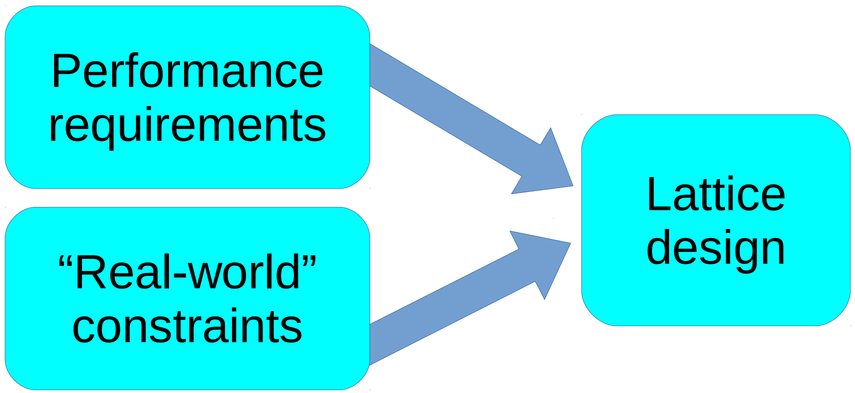
- Alexei Blednykh (NSLS-II)
- Michael Borland
- Bran Brajuskovic
- Jason Carter
- Herman Cease
- Yong-Chul Chae (retired)
- Glen Decker
- Louis Emery
- Jason Lerch
- Medani Sangroula
- Ben Stillwell
- Dean Walter
- Uli Wienands

Outline

- Motivation and purpose
- Introduction to the 42-pm APS-U lattice
- Heating loads from synchrotron radiation
- Wakefields and impedances
  - Introduction
  - Collective effects driven by longitudinal wakefields
  - Examples: photon absorbers and the BPM-bellows assembly
  - Rf heating concerns
  - Collective effects driven by transverse wakefields
- Joe Calvey's turn: gas scattering lifetime and ion effects

Motivation and purpose

- Accelerator design is a highly collaborative effort



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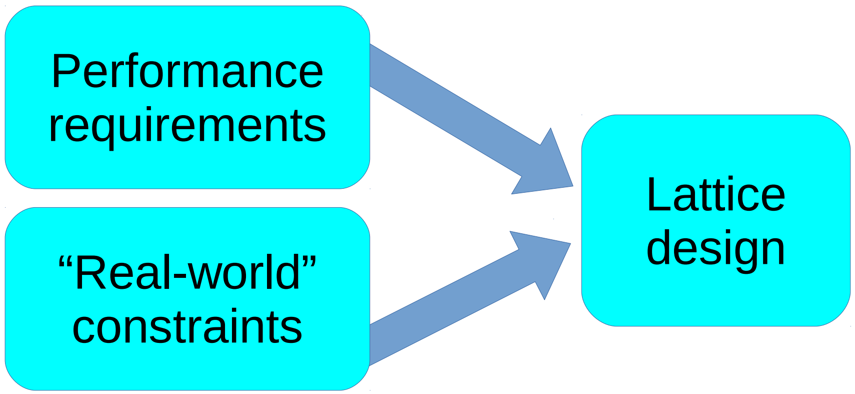

Theoretical storage ring: Done!

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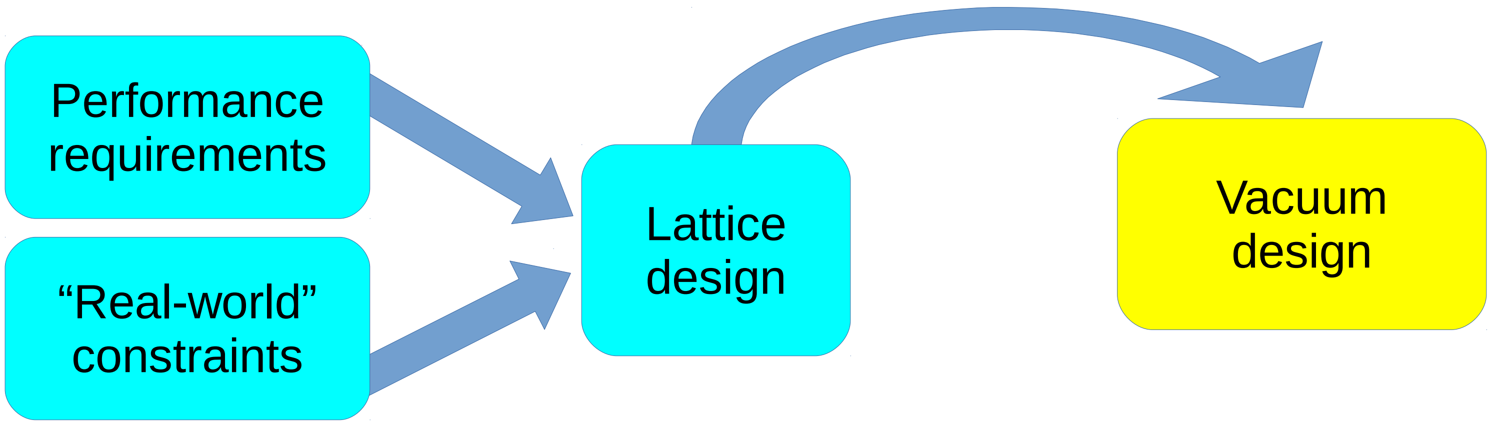

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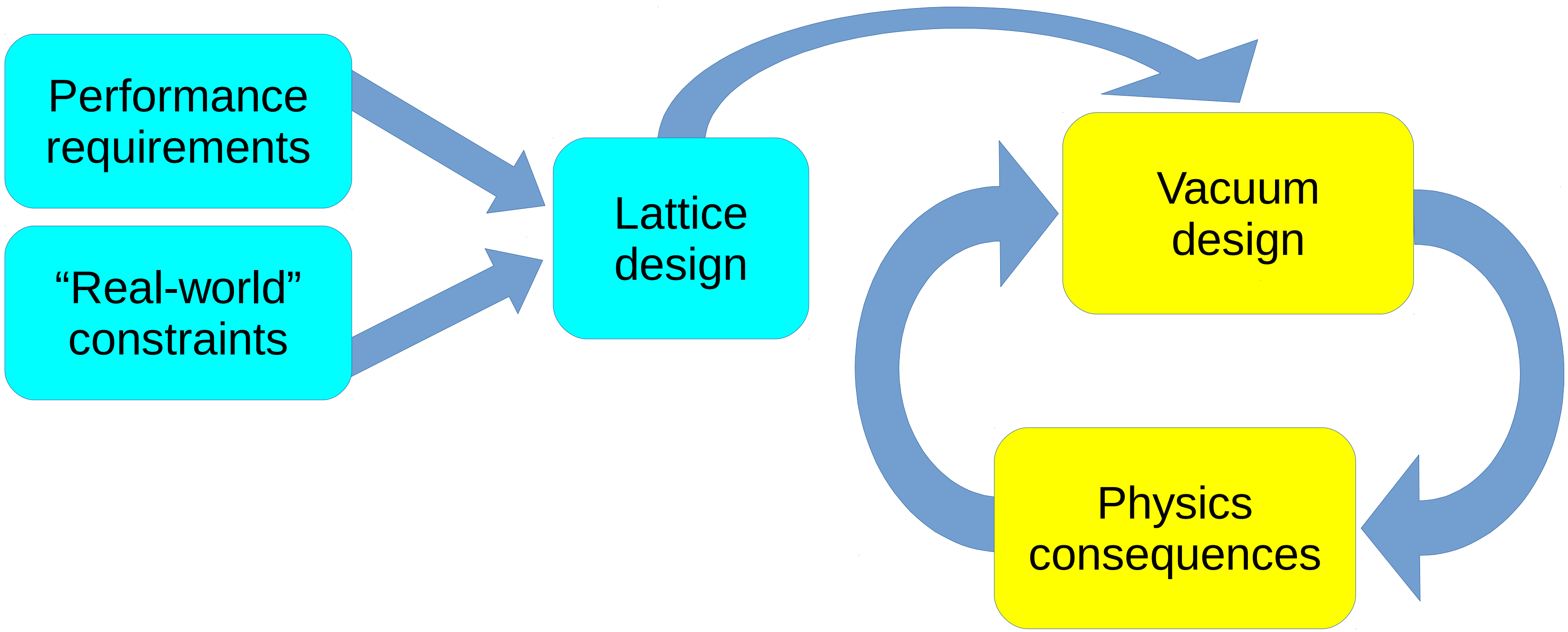

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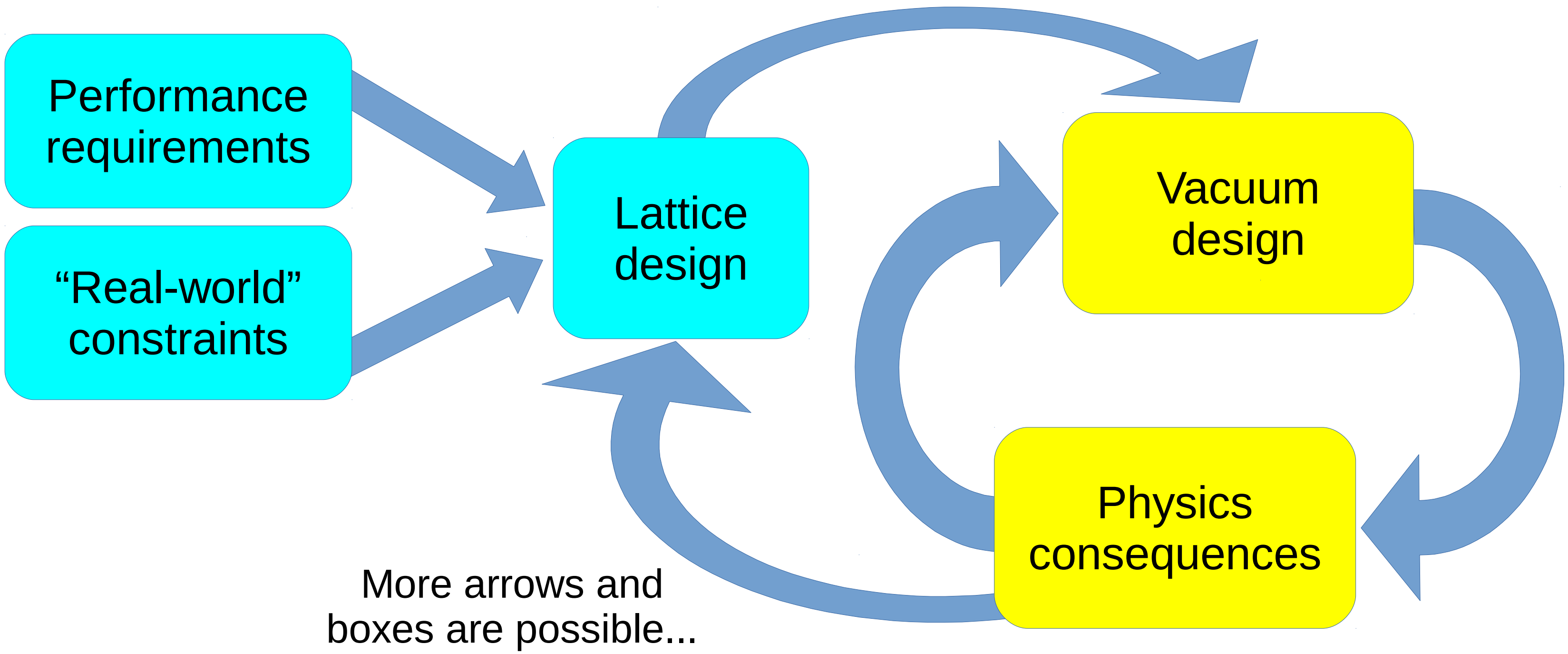

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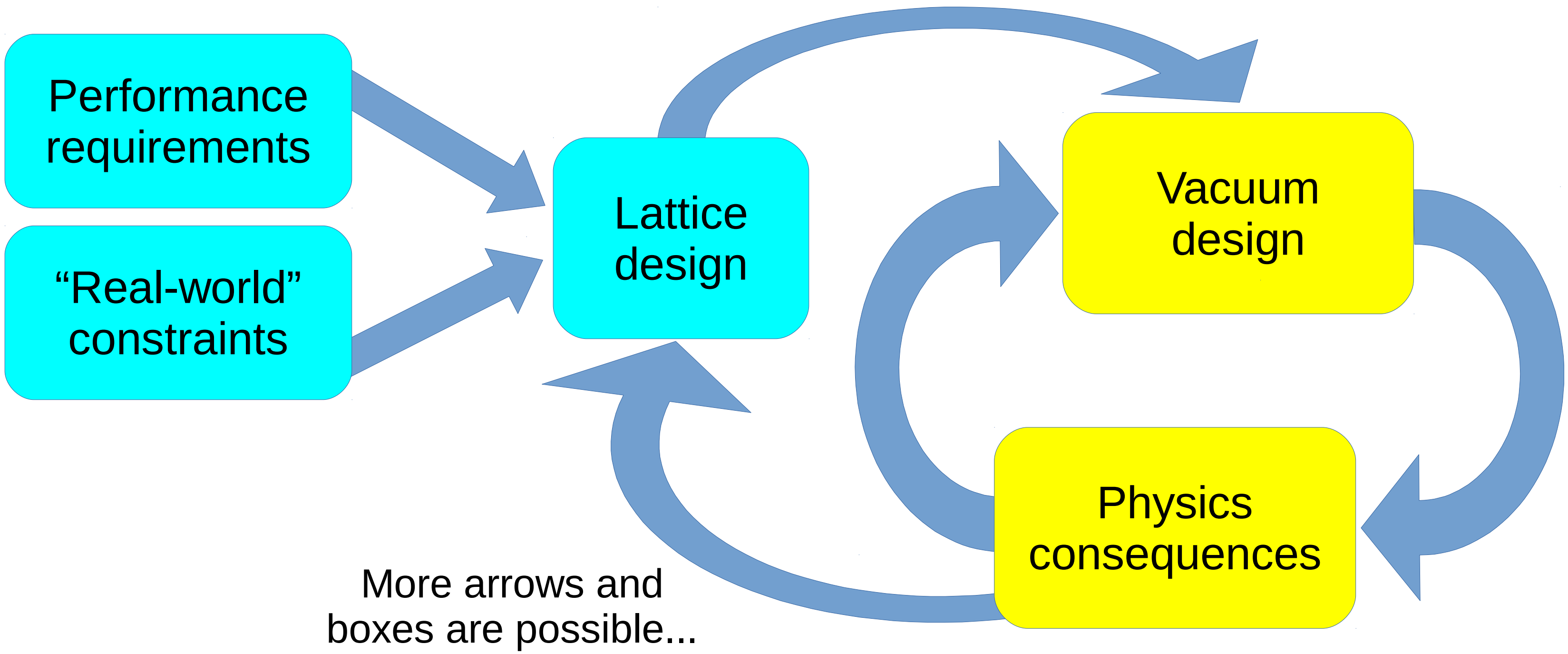
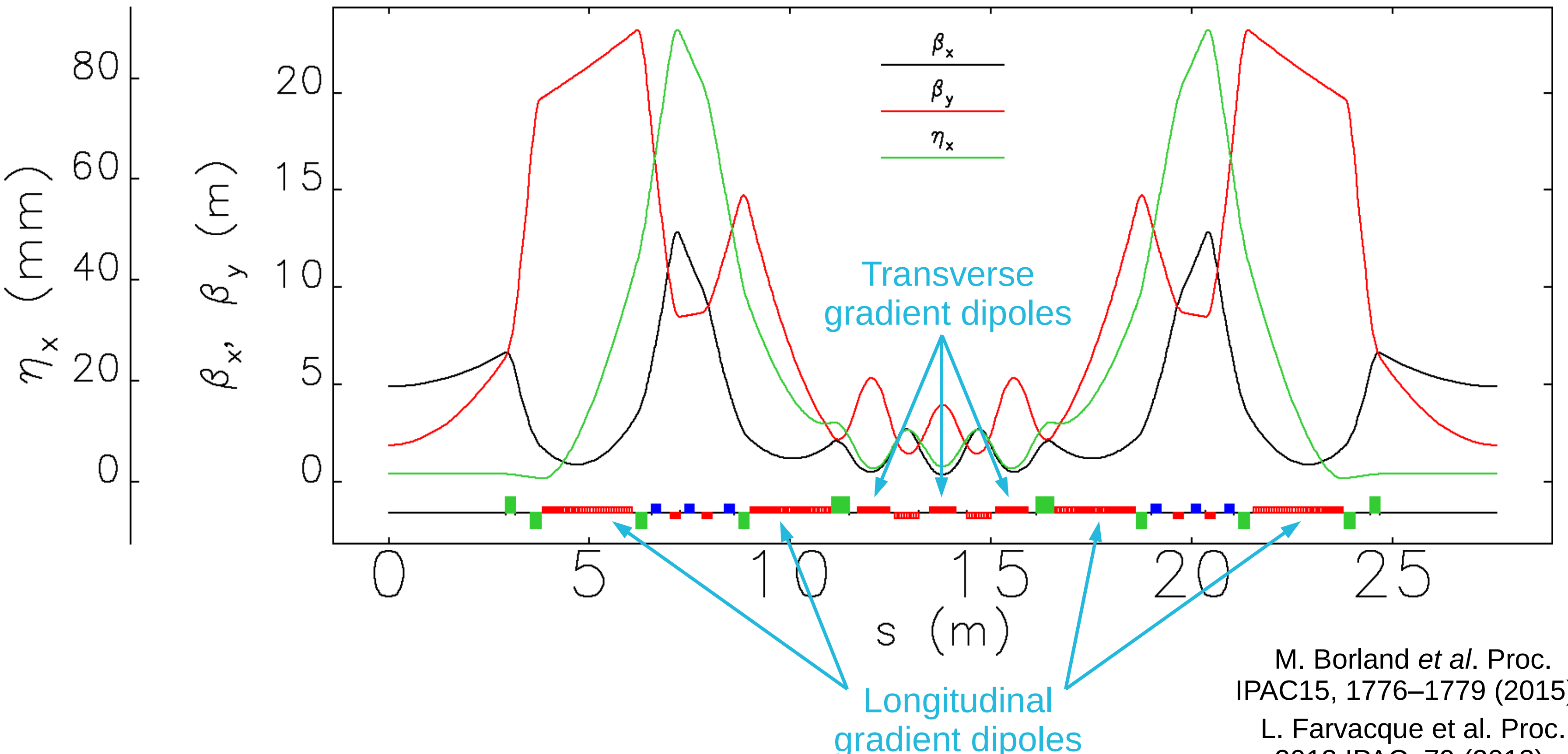


- We thought it might be useful to prelude Ben Stillwell's vacuum design seminar with some of the relevant physics

42-pm 7-bend achromat lattice with reverse bends



M. Borland *et al*. Proc. IPAC15, 1776–1779 (2015);

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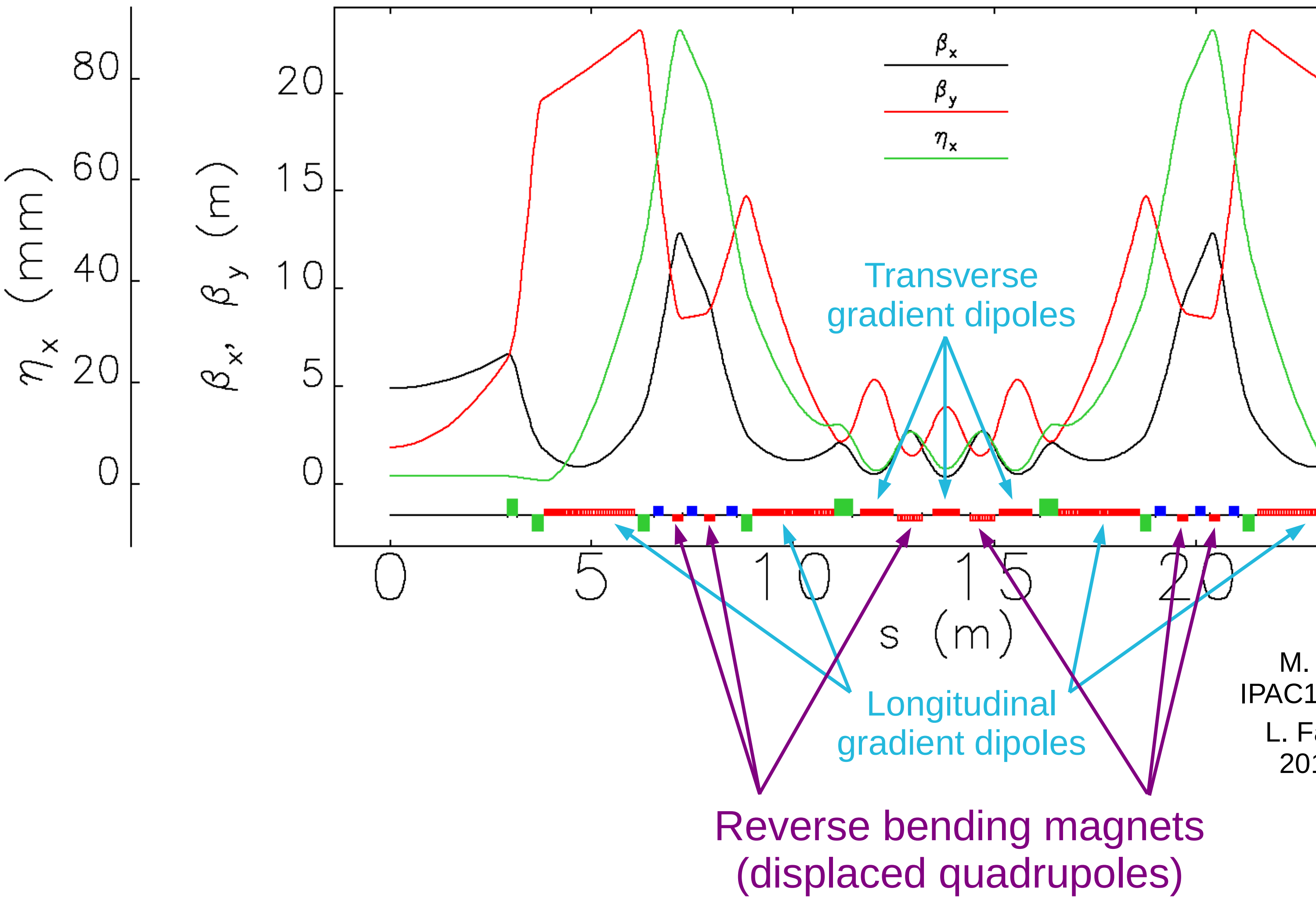

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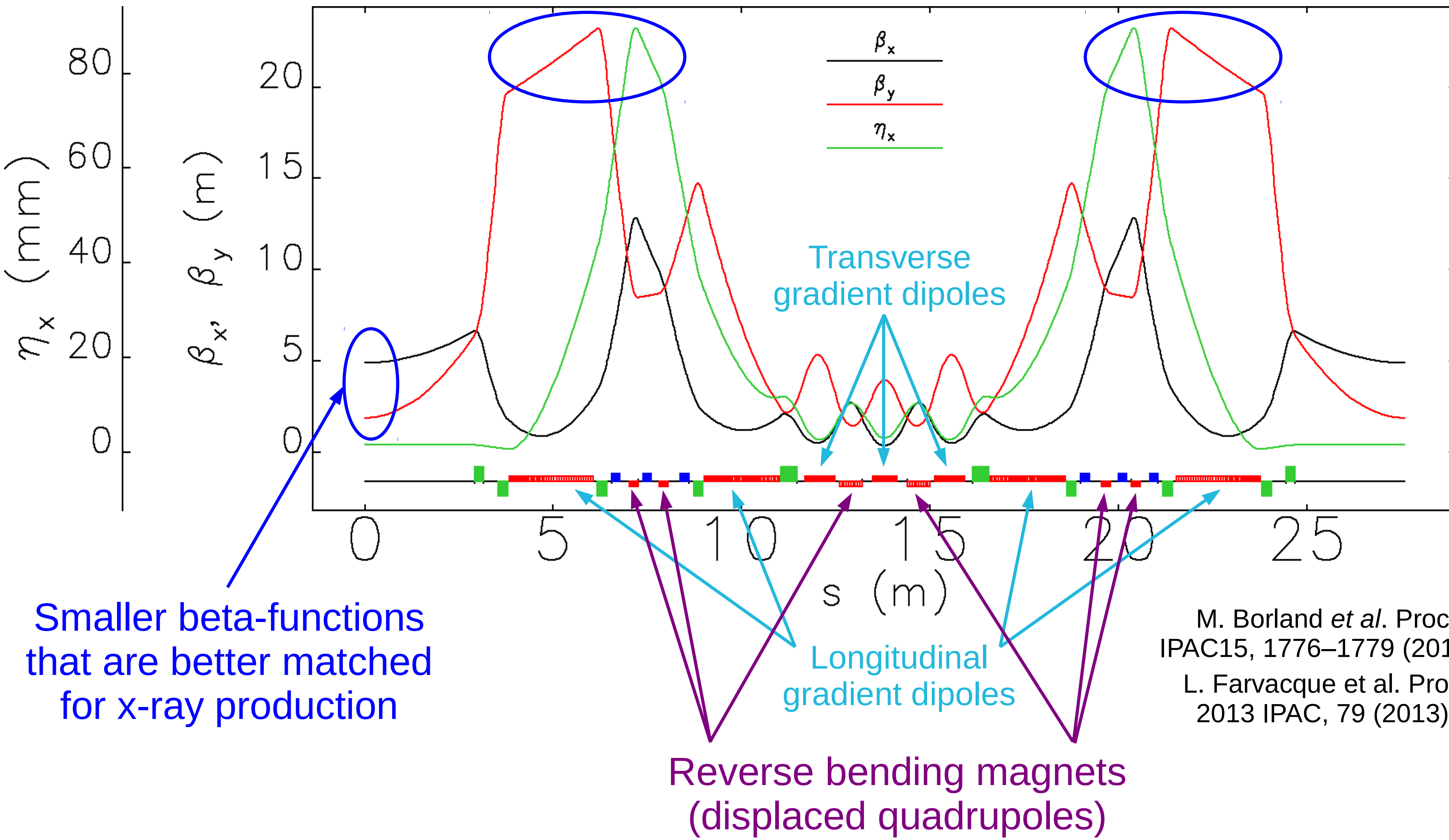
Larger beta functions and dispersion to reduce sextupole strength



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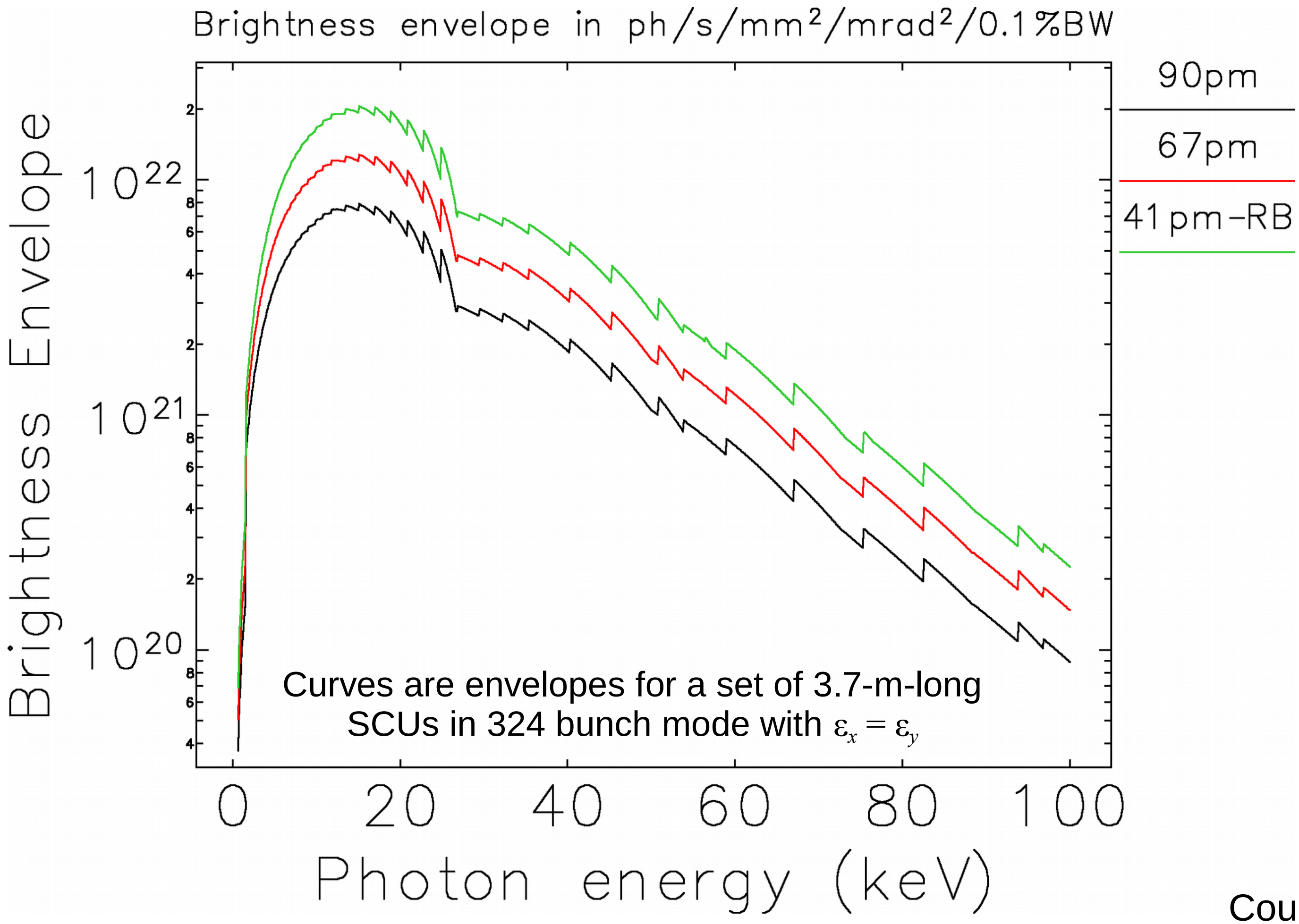
X-ray brightness increases by ~60% by going from the 67-pm to the 42-pm lattice



Courtesy
M. Borland

Synchrotron radiation heating

- Each of the 7 gradient dipoles radiate copious x-rays, and the 6 reverse bending magnets add additional synchrotron radiation loads
- Vacuum engineers have taken the lead on computing synchrotron radiation loads
  - Ray tracing tools within CAD models
  - SynRad modeling of emission, propagation, and scattering (Jason Carter)
  - Inclusion of mis-steered beams

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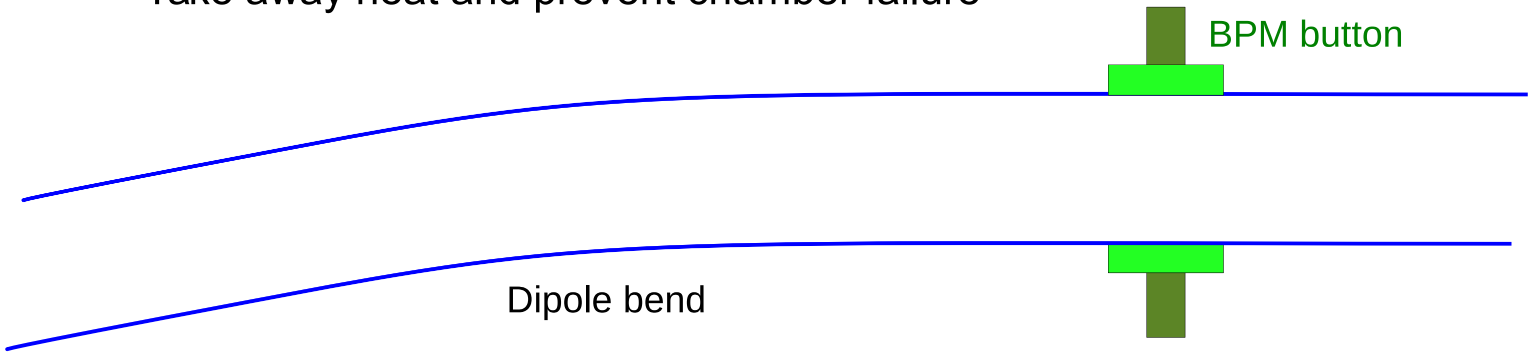

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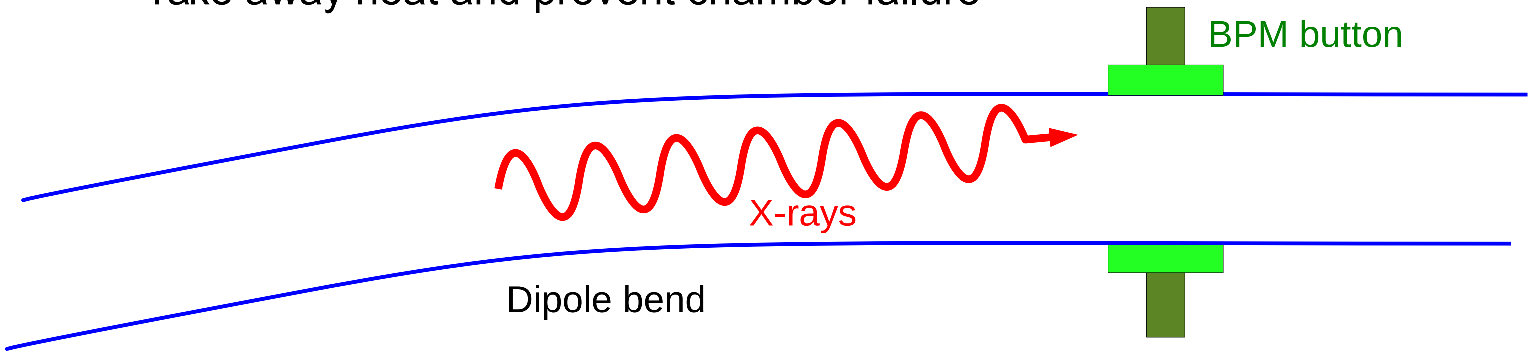

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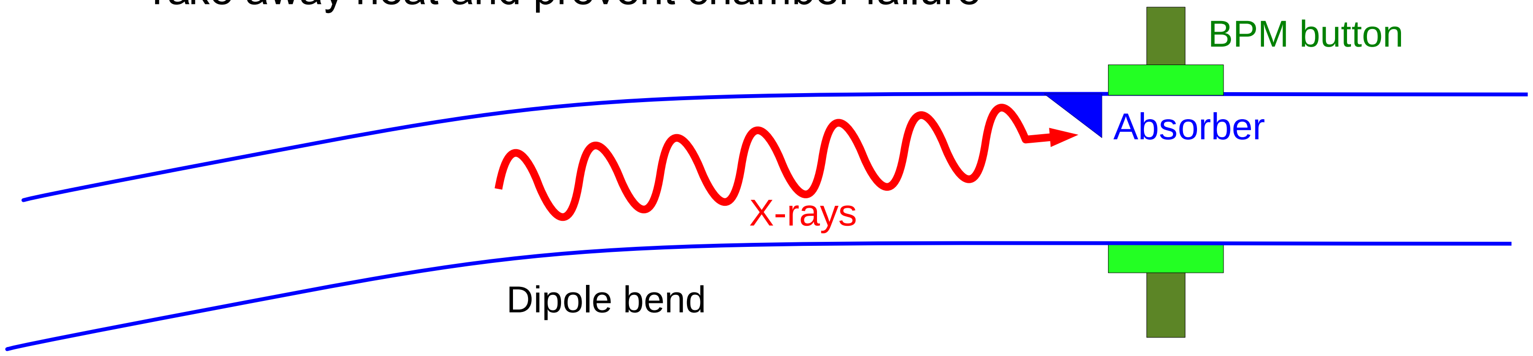

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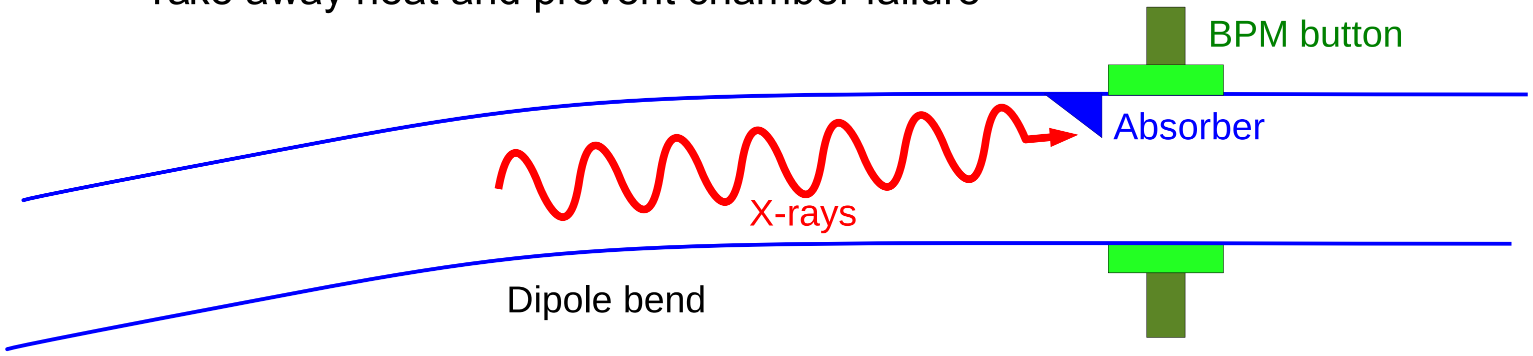
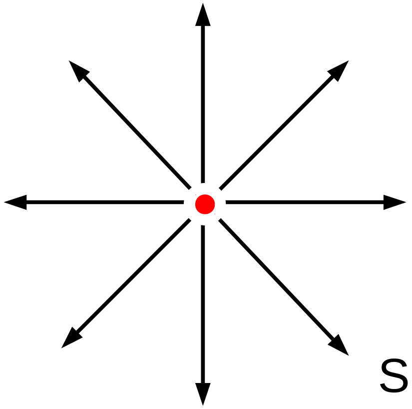


- Electrons produce wakefields as they pass by absorbers (or any other vacuum component), which can perturb trailing electrons and result in rf heating, instabilities, and potential beam loss

Coulomb field of a relativistic charge



$v = 0$

Spherically symmetric

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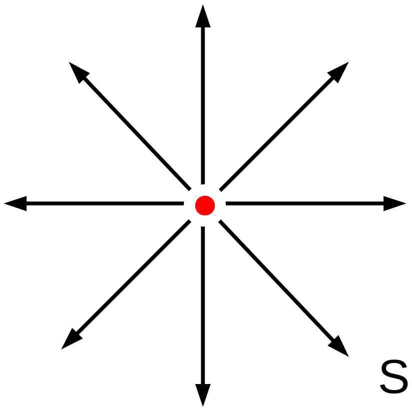

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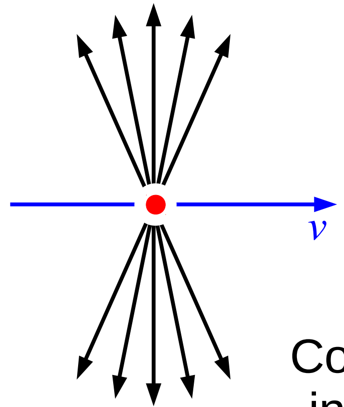

$\gamma >> 1$

Compressed into angle $\sim 1/\gamma$

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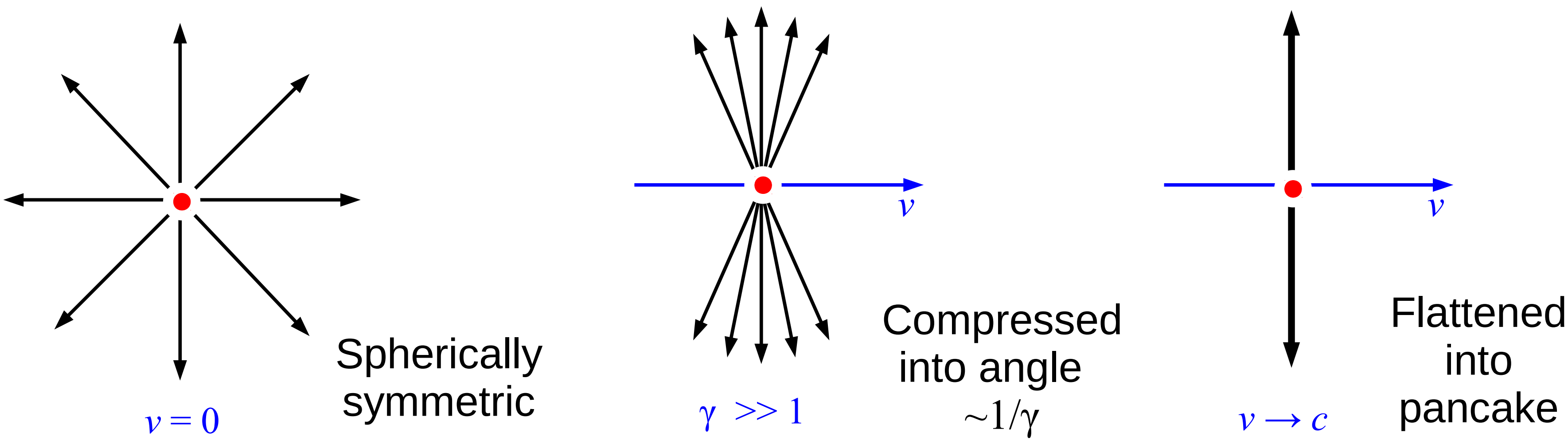

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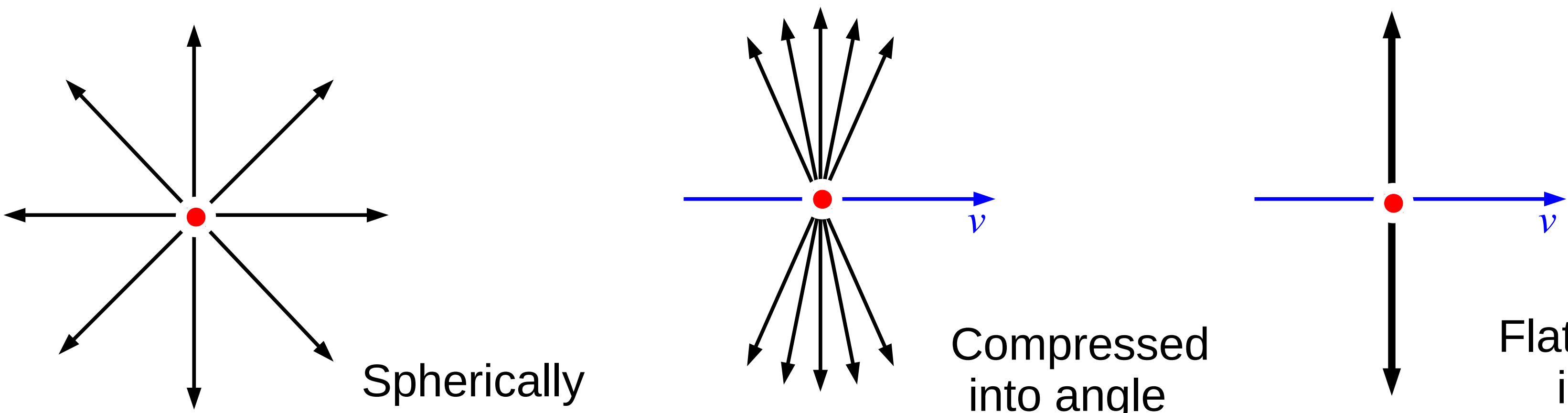
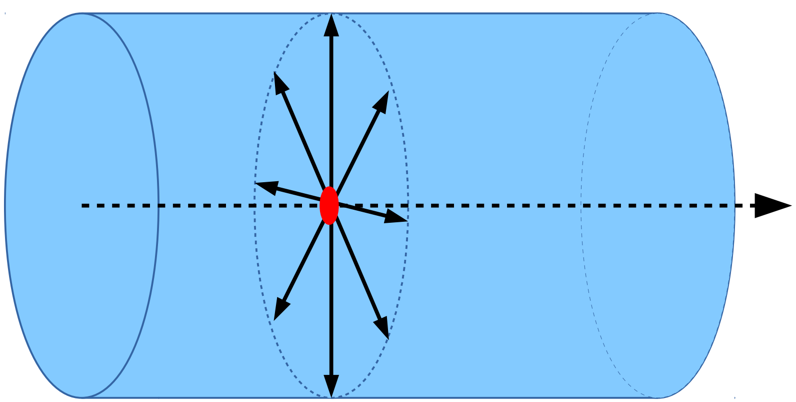


$v = 0$ Spherically symmetric

$\gamma >> 1$ Compressed into angle $\sim 1/\gamma$

$v \to c$ Flattened into pancake

Perfectly conducting chamber



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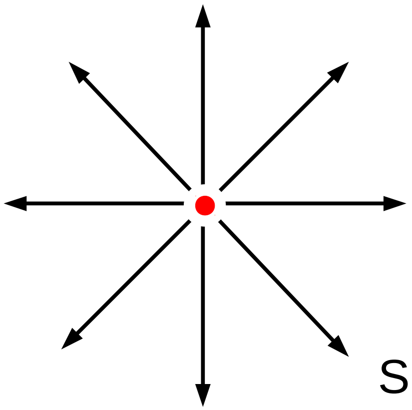

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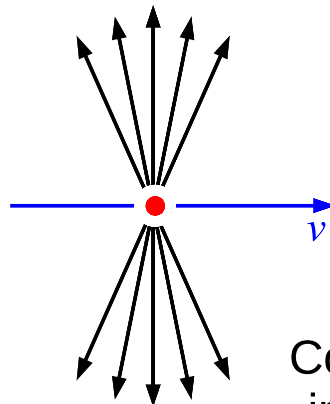

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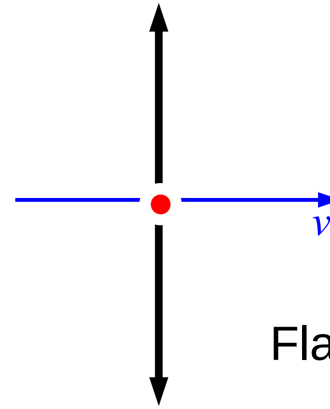

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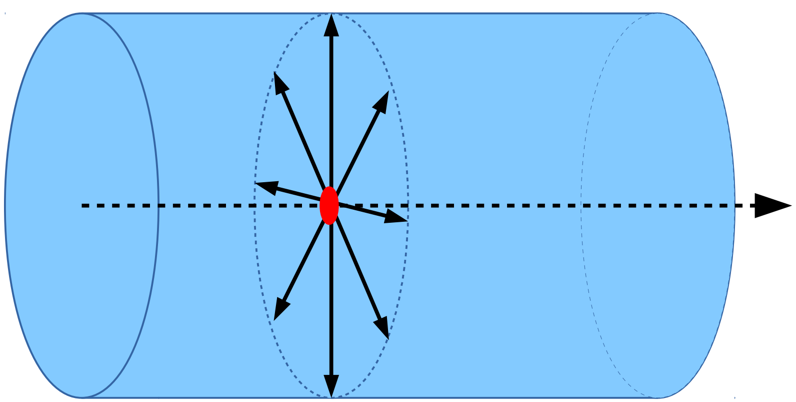
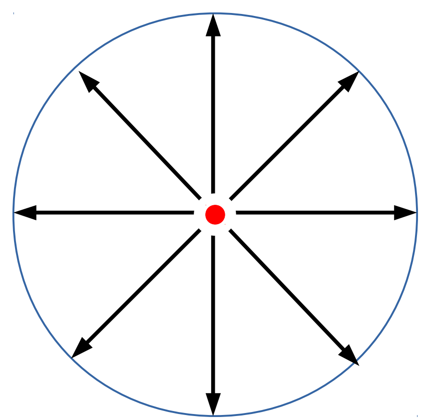
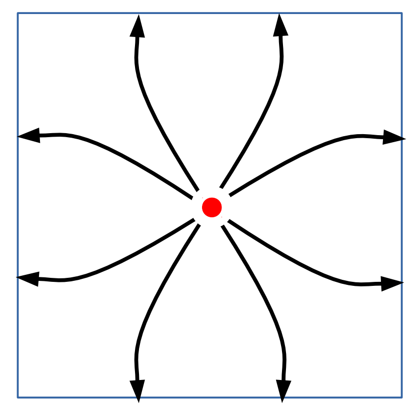
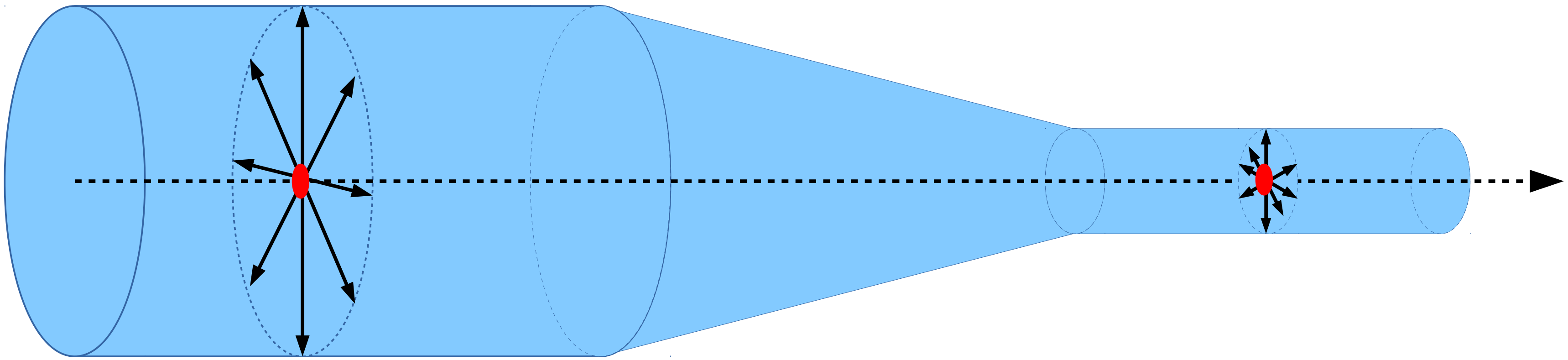


Field lines can be arranged to satisfy appropriate boundary conditions for arbitrary geometries





Geometric wakefields/impedance are generated by changes in the vacuum chamber cross section



Changes in vacuum chamber cross section → Rearrangement of fields to satisfy new boundary conditions

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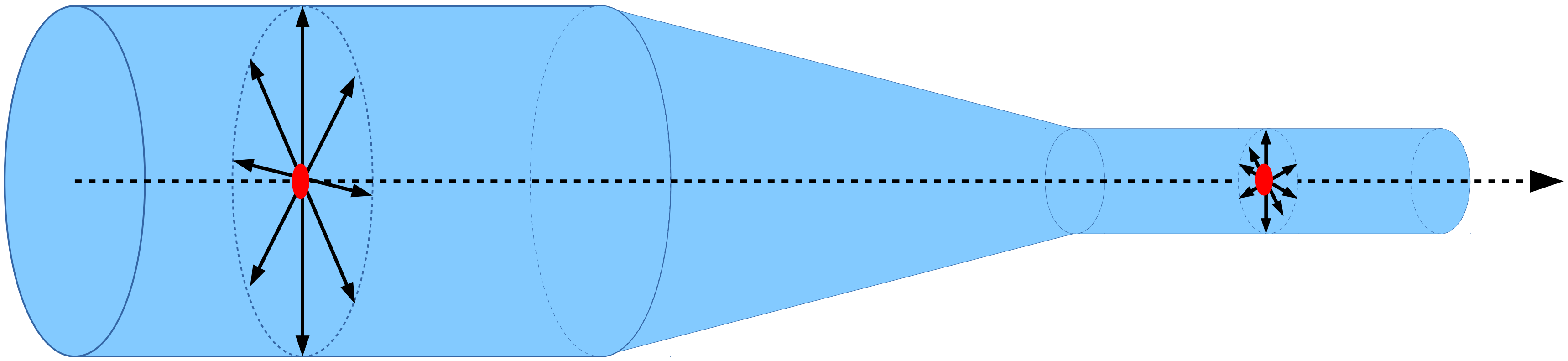

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- The resulting electromagnetic fields lead to wakefields that are behind the exciting charge (since $v \approx c$)
- The magnitude of the wakefield depends on the change in the chamber cross section and how fast that change occurs

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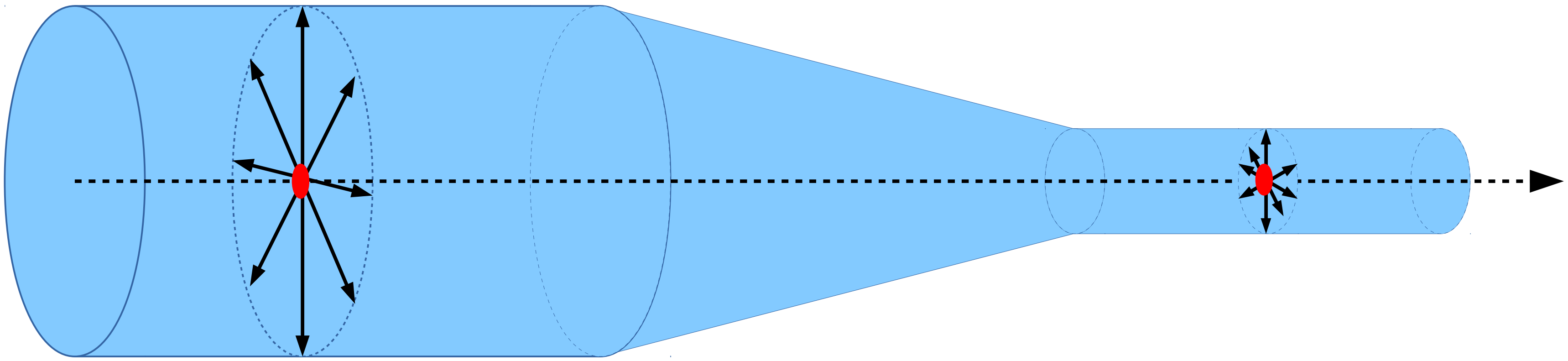

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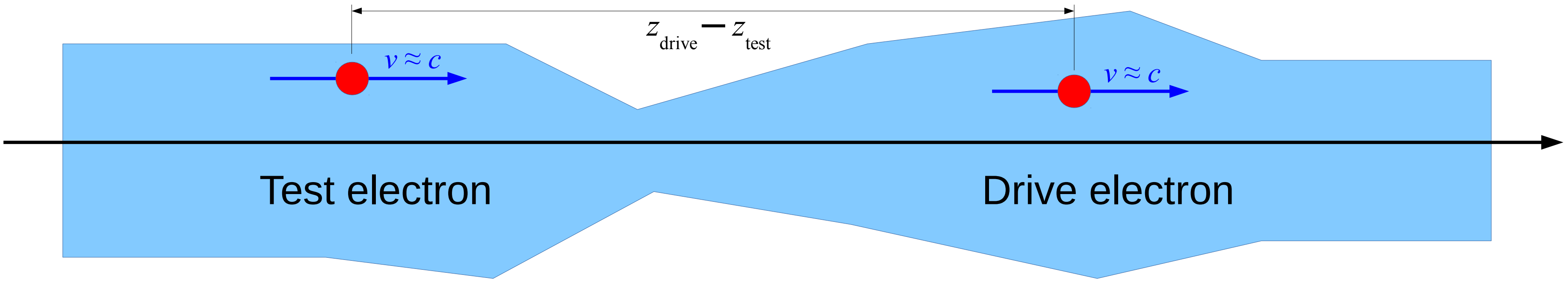
- The resulting electromagnetic fields lead to wakefields that are behind the exciting charge (since $v \approx c$)
- The magnitude of the wakefield depends on the change in the chamber cross section and how fast that change occurs
- In addition, there are resistive wall wakefields due to the finite resistivity of the chamber walls

Longitudinal wakefields and impedances



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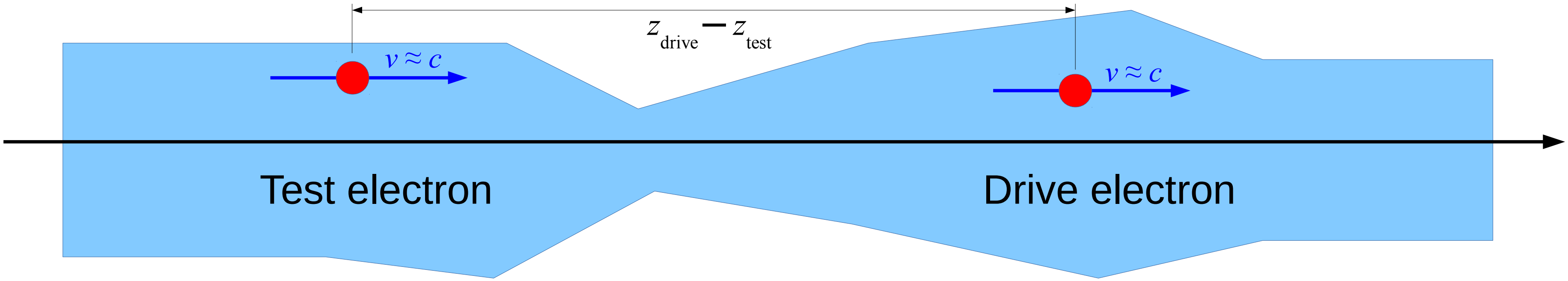

Longitudinal wakefields $W_{\parallel}$ characterize the change in the test particle's energy due to the electric field from the drive electron:

$$\Delta\gamma = -\frac{e}{mc^2}\int_{-\infty}^{\infty} ds\; E_{\parallel}(x,y,z;s) \equiv -\frac{e^2}{mc^2}W_{\parallel}(x,y,z)$$

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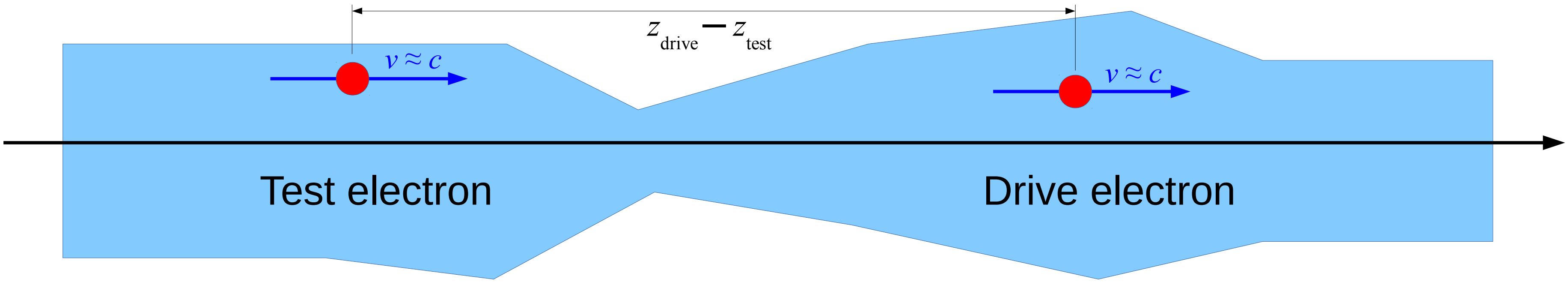

Longitudinal wakefields $W_{\|}$ characterize the change in the test particle's energy due to the electric field from the drive electron:

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$W_{\|}$ is approximately a function of only the difference in longitudinal positions:

$$\Delta\gamma_{\text{test}} \approx -\frac{e}{mc^2} W_{\|}(z_{\text{drive}} - z_{\text{test}})$$

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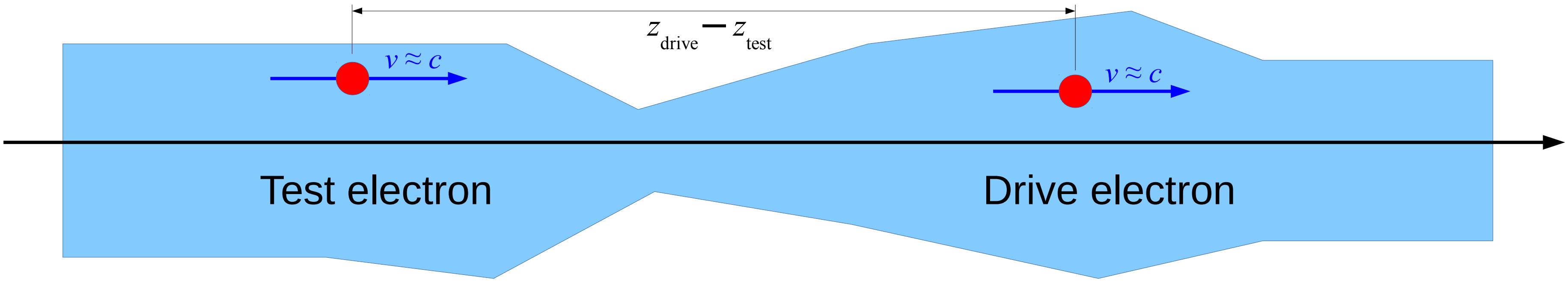

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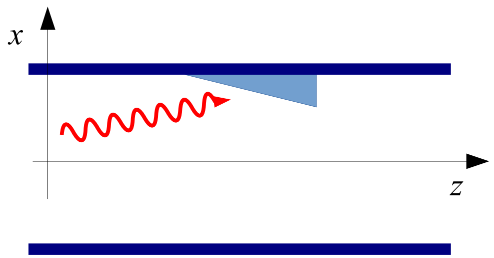
Impedance is the Fourier transform of the wakefield with respect to $\tau = z_{\text{drive}} - z_{\text{test}}$:

$$Z_{\|}(k) = \frac{1}{c}\int d\tau\; e^{-ik\tau}W_{\|}(\tau)$$

Example: in-line photon absorbers



Not great design:

1. Tapers should come both in and out (slope < 0.1 if possible)
2. Lack of mirror symmetry in x drives transverse wakefields that could increase emittance

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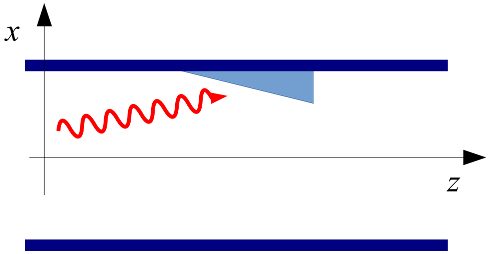

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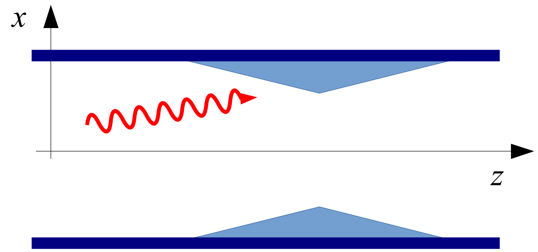

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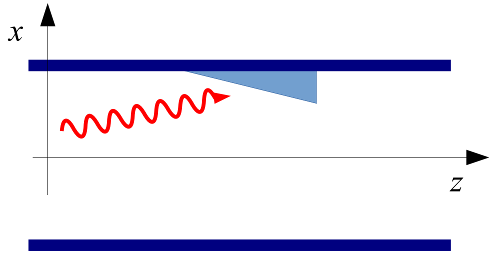

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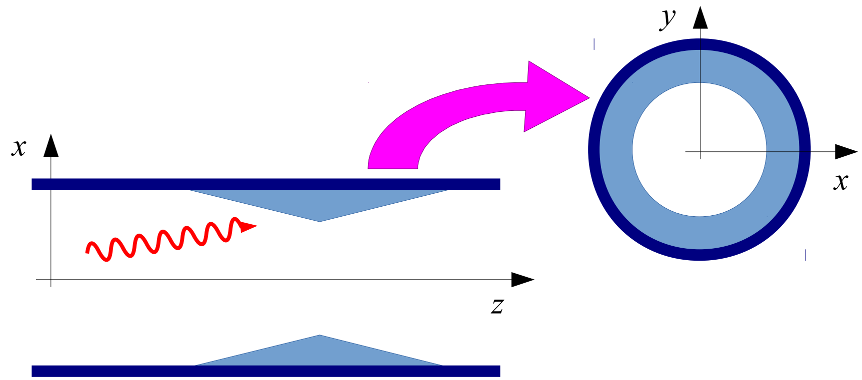

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2. Present design for absorbers in FODO section

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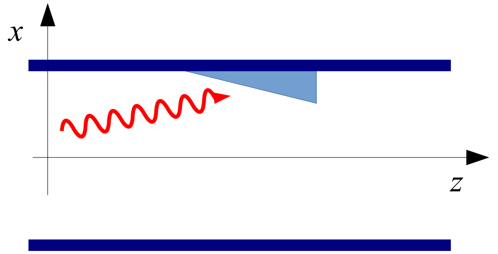

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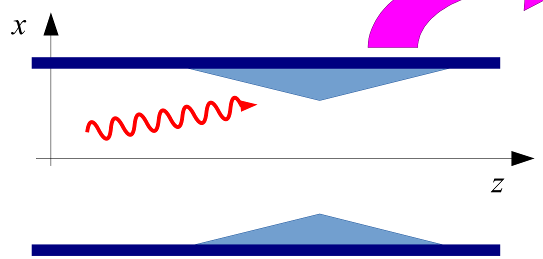

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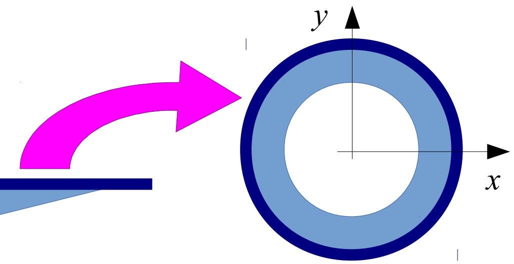

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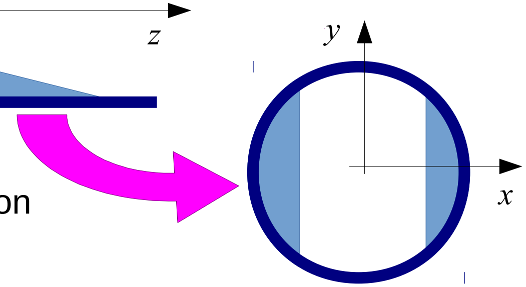

Wedge:

1. Smaller impedance
2. Present default design

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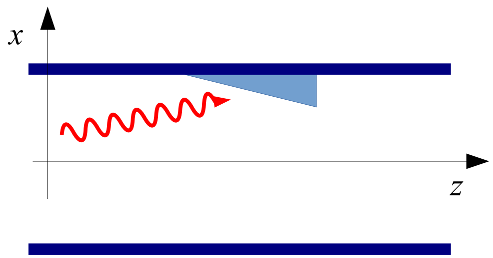

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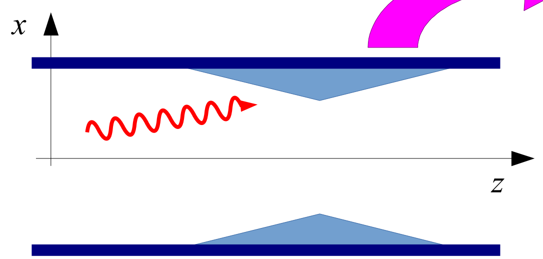
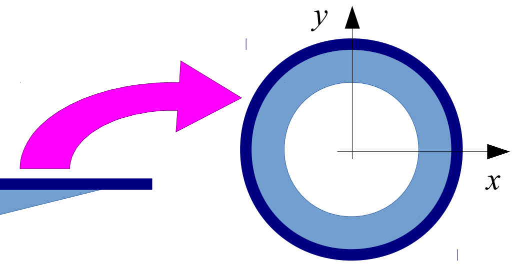
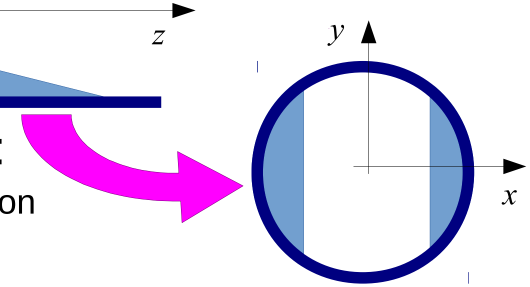
$n = f / f_0$







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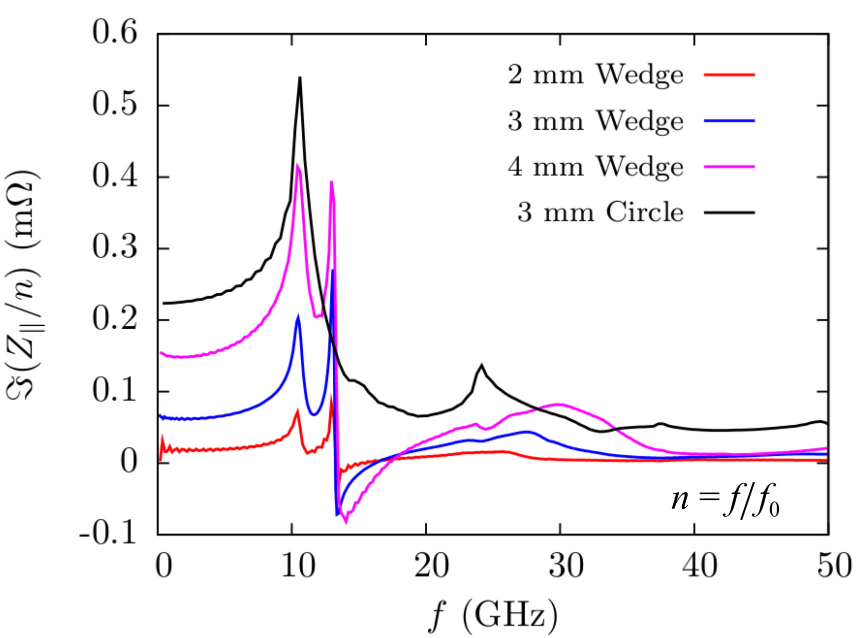

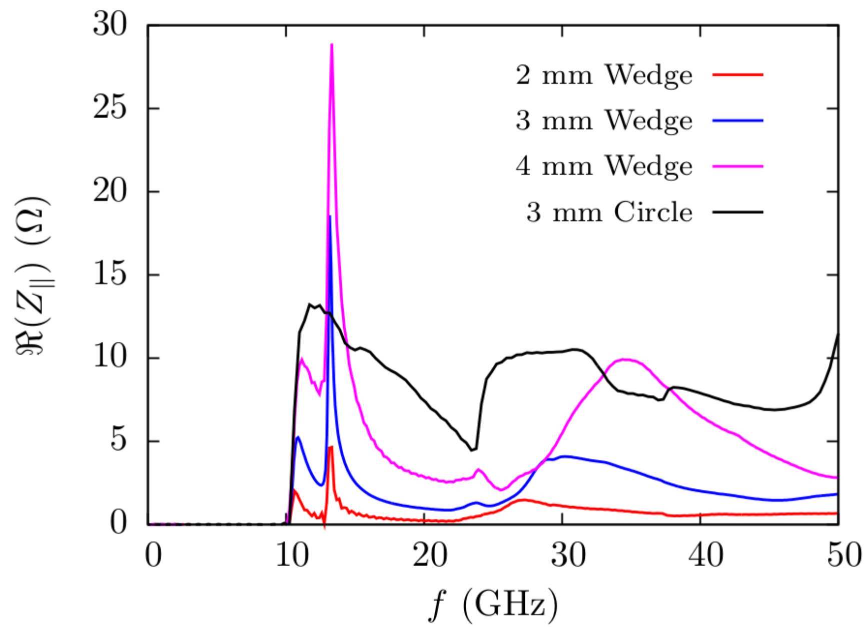

Bunch lengthening and microwave instability threshold largely set by $\mathrm{Im}\left[Z_{\|}(k)/k\right]$

Bunch lengthening and microwave instability threshold largely set by Im$[Z_{\|}(k)/k]$

Impedance source	Number	$\Im(Z_{\|})/n$ (Ω)
In-line absorber	760	0.060
BPM-bellows	560	0.048
Gate valve	160	0.020
Rf transitions	3	0.018
Flange	1880	0.011
Inj/ext kickers	8	0.0075
Crotch absorber	80	0.0070
ID transition	40	0.0018
Pumping cross	200	0.0015
Small-gap ID BPM	30	0.0013
352 MHz rf-cavity	10	0.001
Total	NA	0.18

Bunch lengthening and microwave instability threshold largely set by Im$[Z_{\|}(k)/k]$

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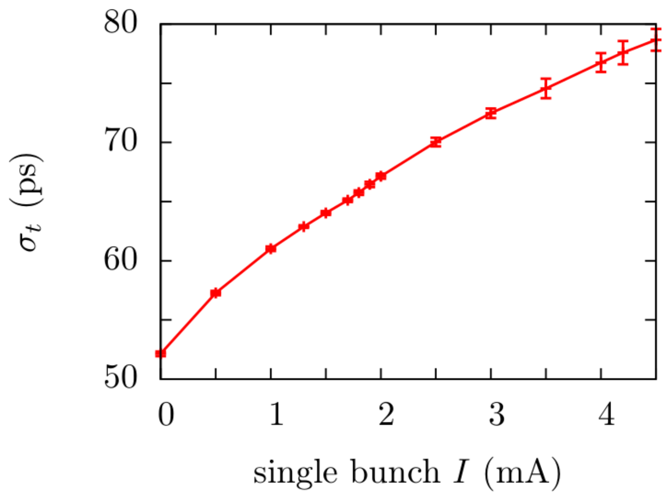
352 MHz rf-cavity	10	0.001
Total	NA	0.18



Bunch lengthening and microwave instability threshold largely set by Im$[Z_{\parallel}(k)/k]$

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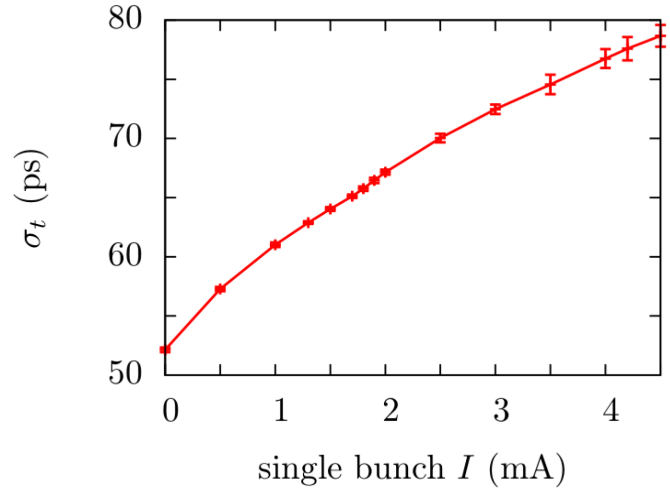

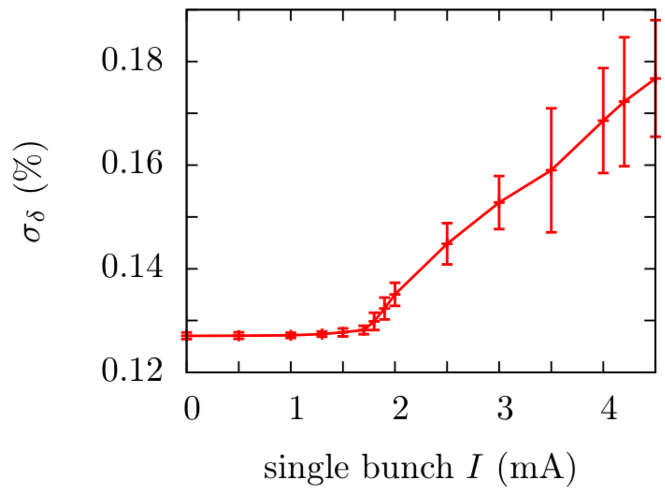

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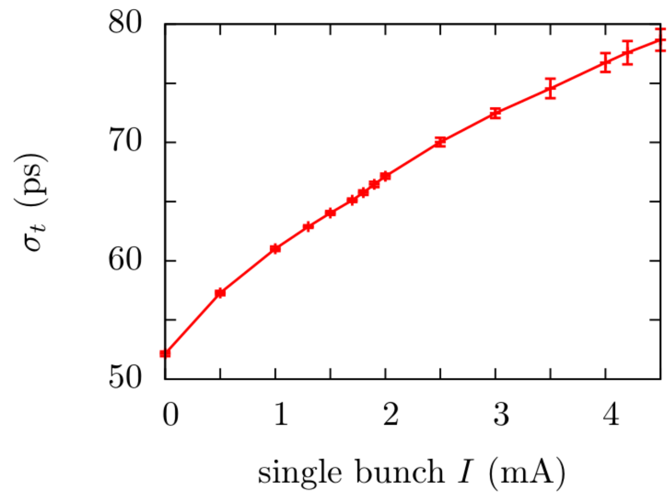

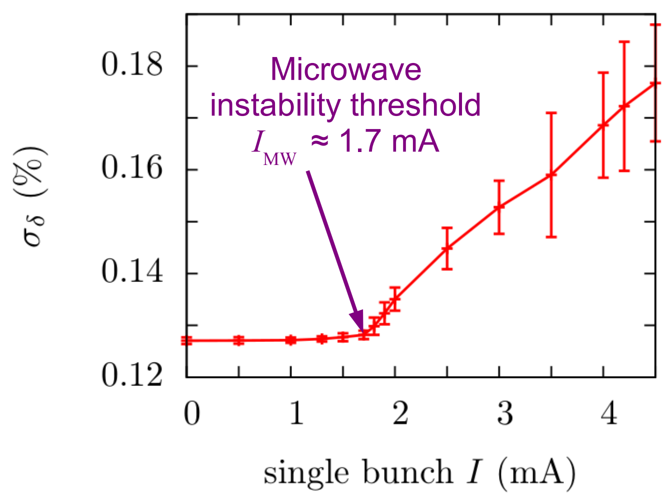

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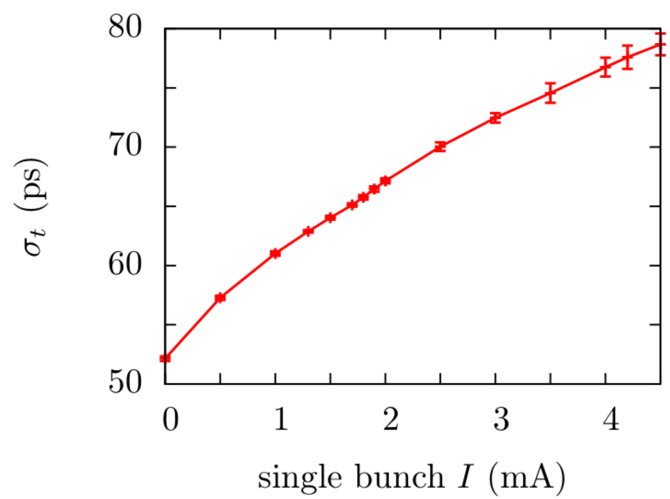
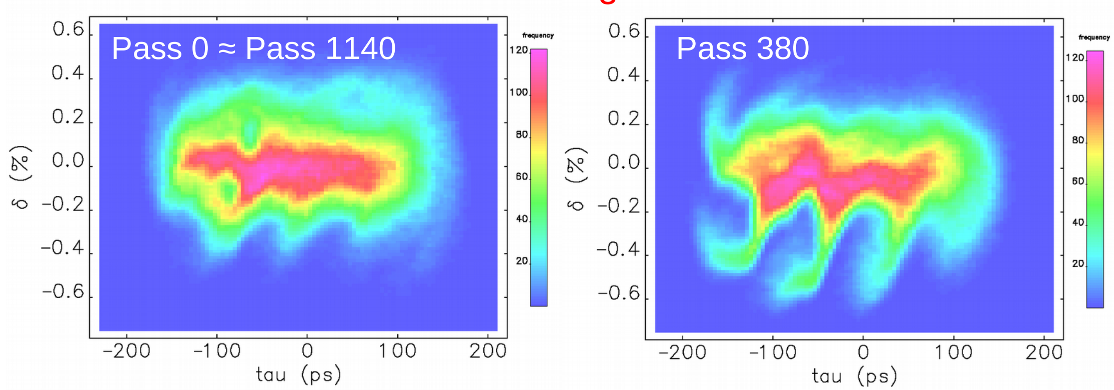
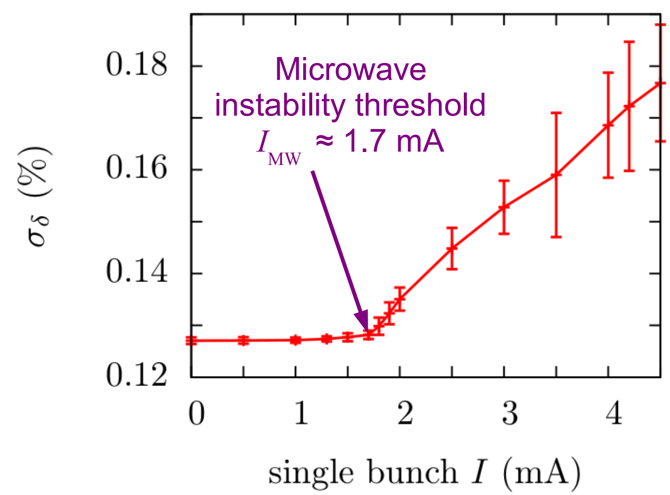


48 bunch mode: single bunch I = 4.2 mA





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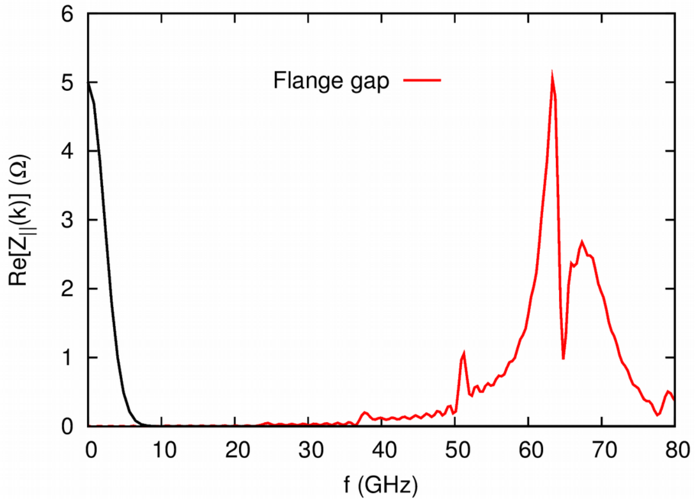

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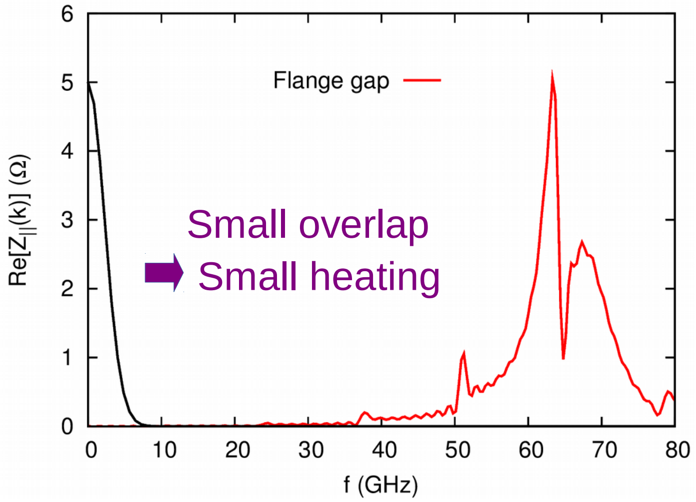

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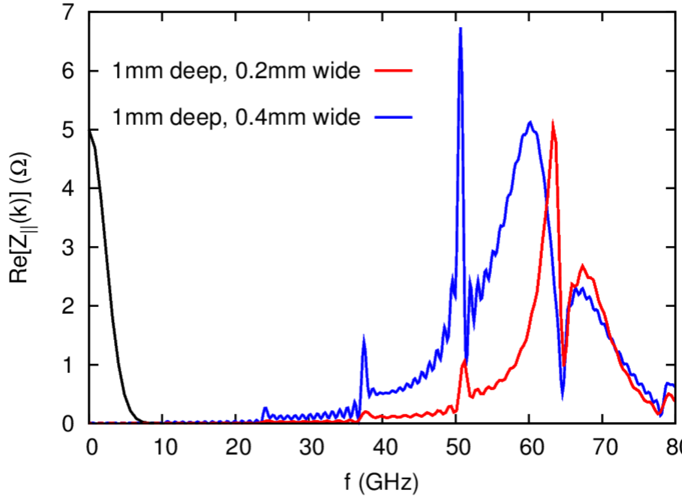

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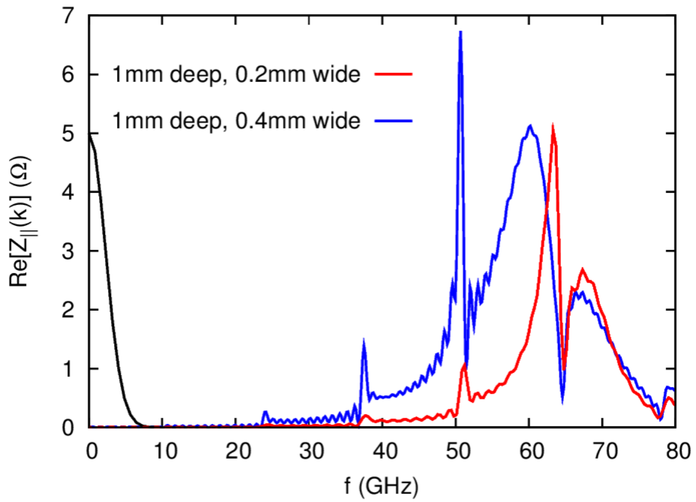

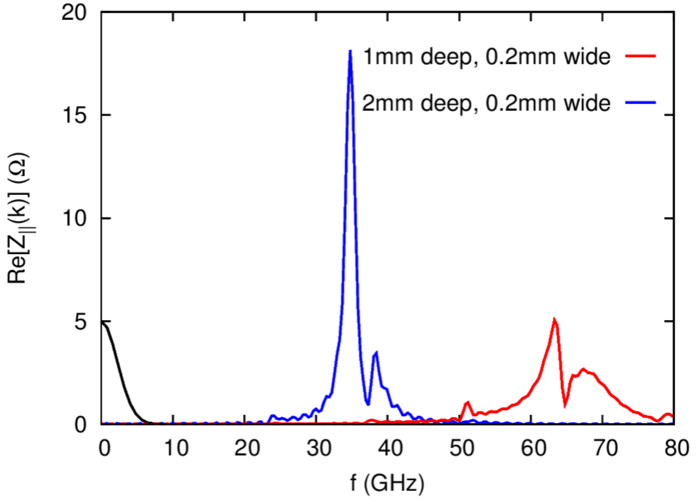

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- Increasing depth is even worse
- Rf shielding is being considered

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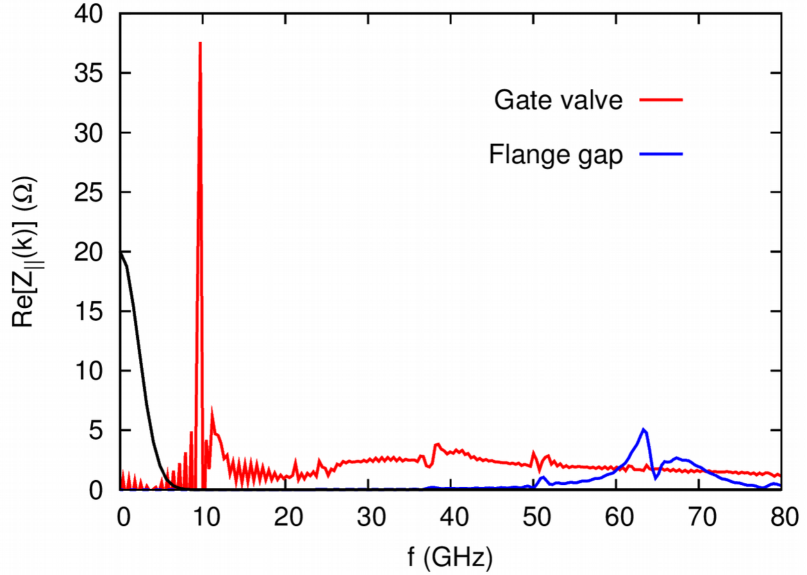
Comparison to Gate valves



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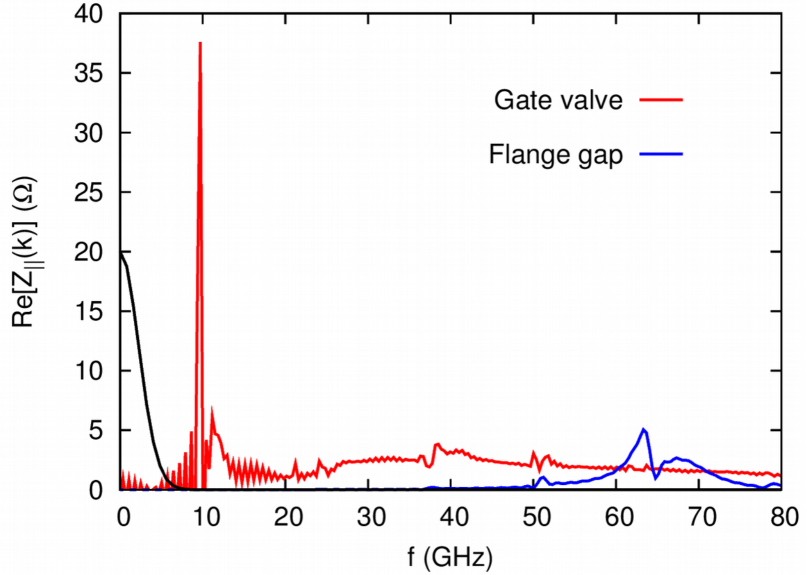
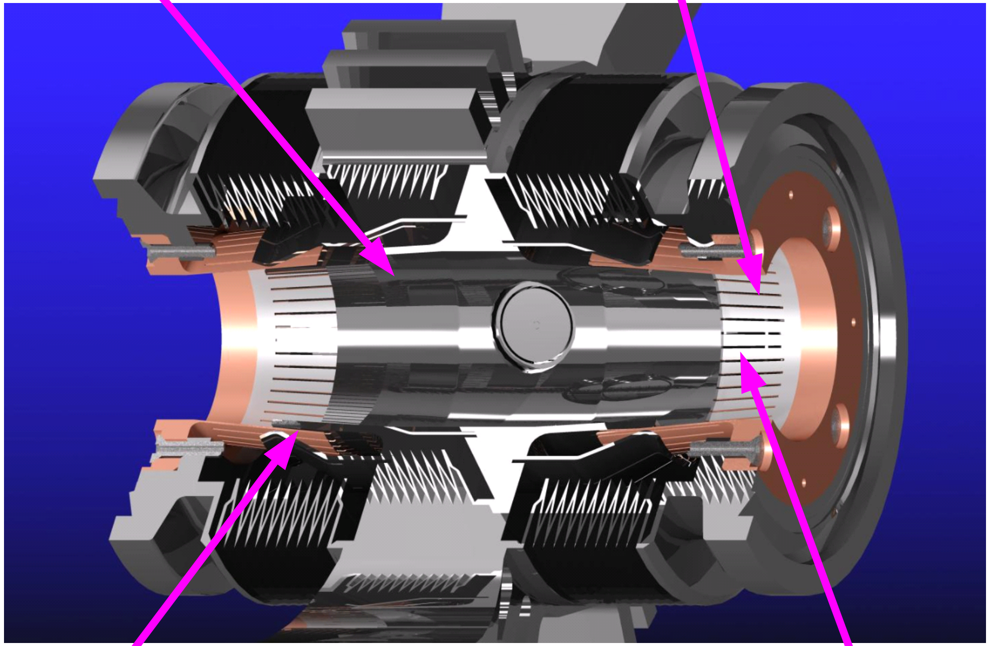


- Gate valves are known to heat up in the present APS
- Resonance has much more overlap with the e-beam spectrum
- Gate valve is a shelf item and its design will probably not be changed

Some impedance issues for the BPM-bellows assembly design

Minimize number and size of cavities to reduce effect of trapped modes

Use small slots to shield low-frequency EM fields



Gradual tapering to different dimensions

Plate poor conductors with good conductors (when possible)

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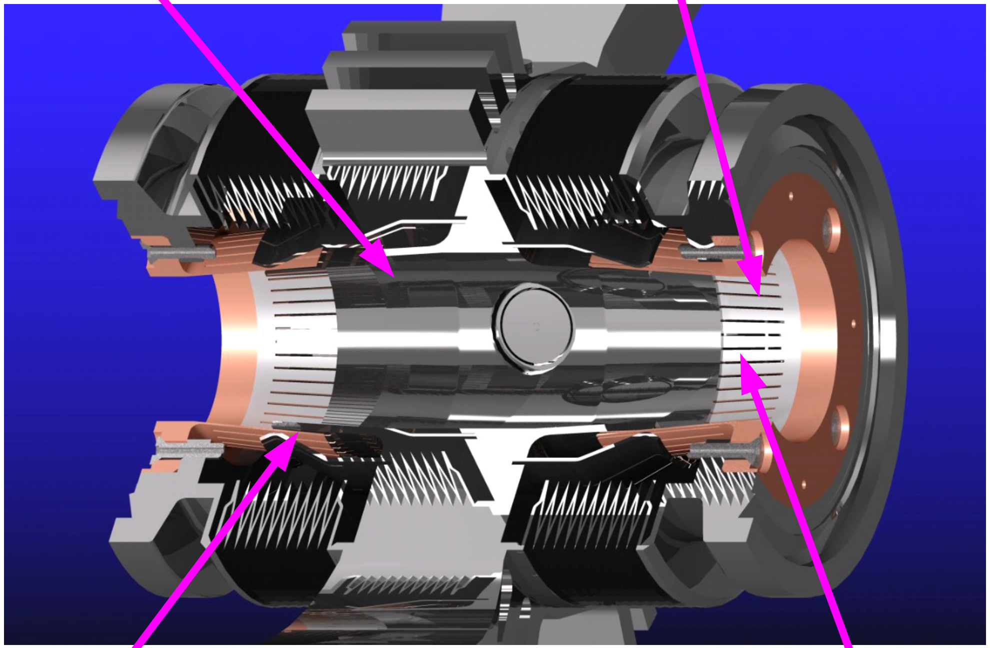

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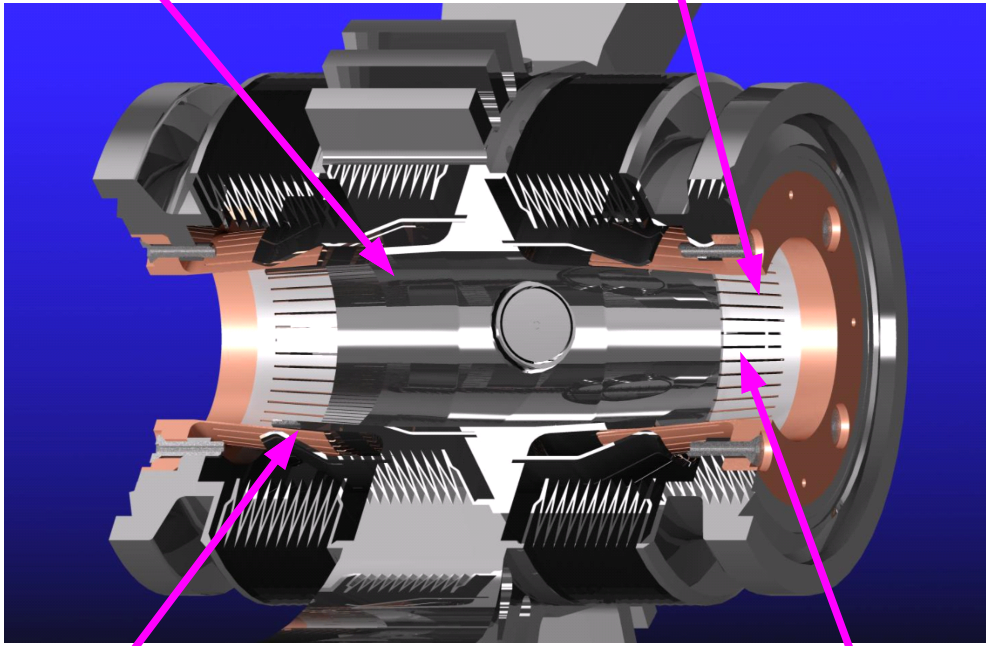

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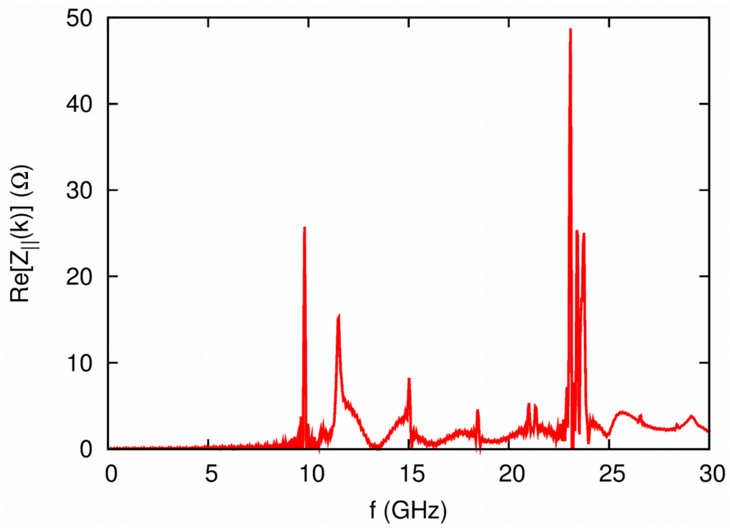
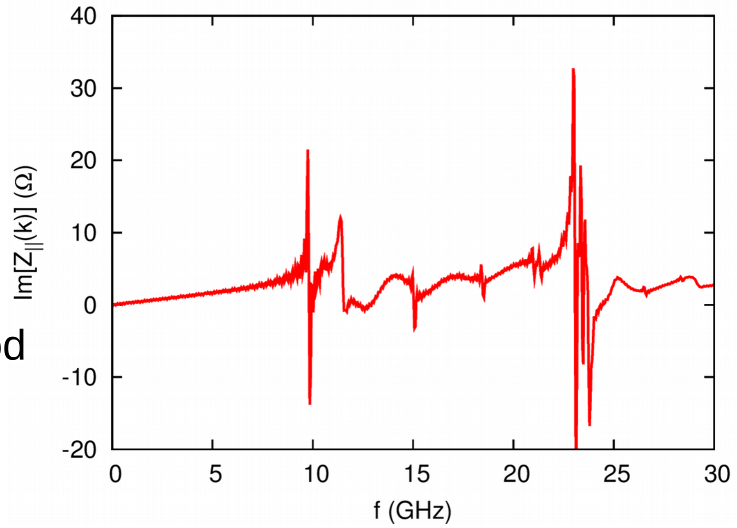
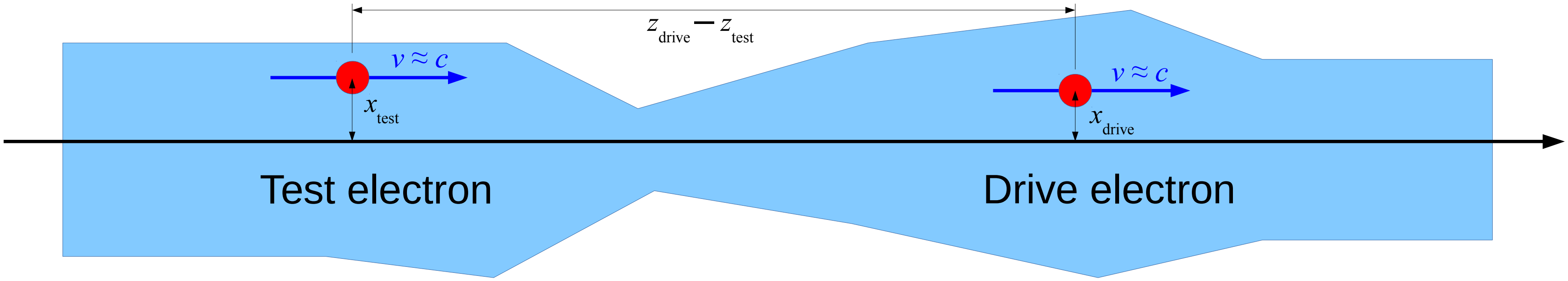




Transverse wakefields and impedances



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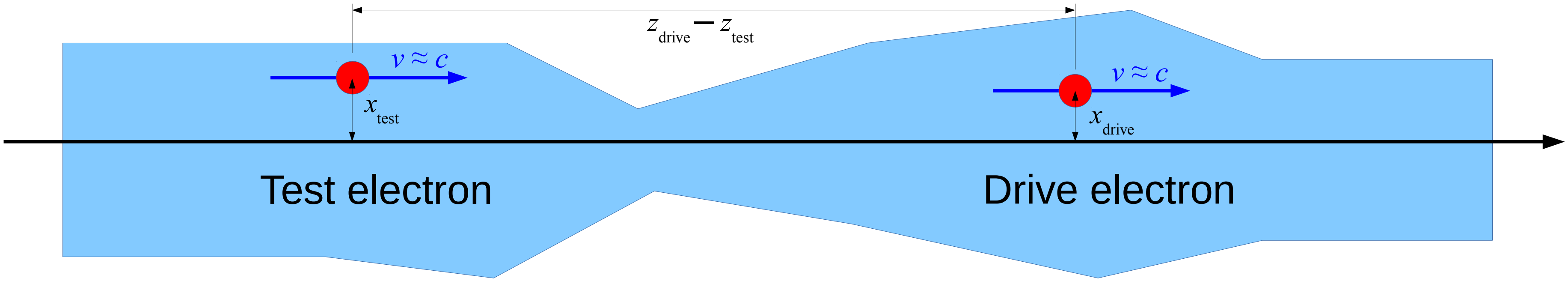

Transverse wakefields $W_\perp$ change the test particle angle: $$\Delta \boldsymbol{x}' = -\frac{e}{\gamma m c^2}\int_{-\infty}^{\infty} ds\,(\boldsymbol{E} + \boldsymbol{v} \times \boldsymbol{B})_\perp \equiv -\frac{e^2}{\gamma m c^2}\boldsymbol{W}_\perp(x,y,z)$$

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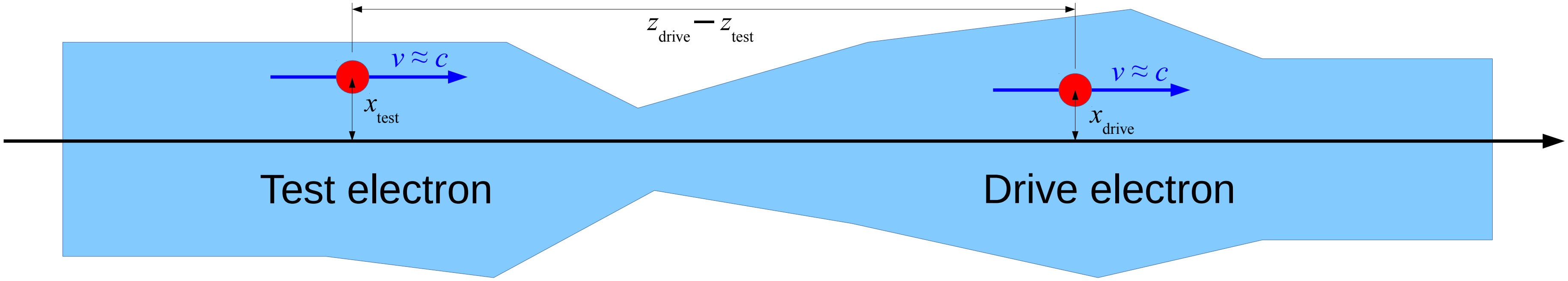

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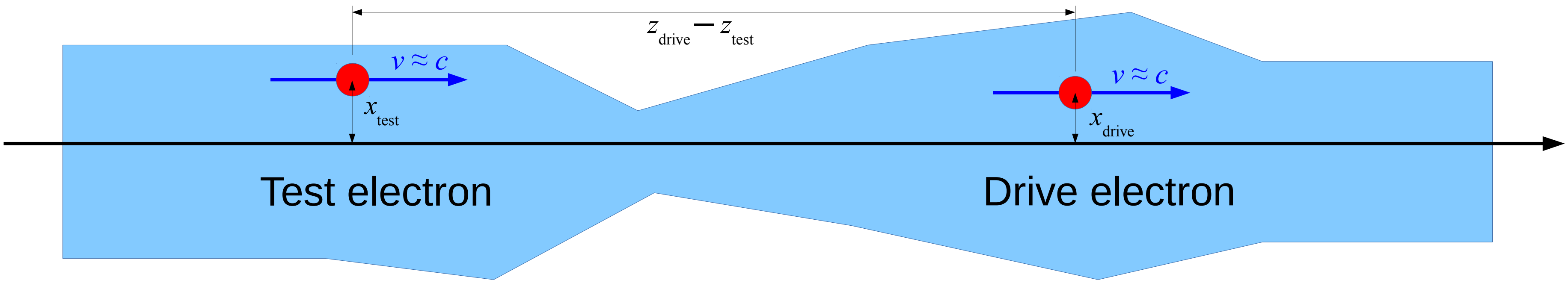

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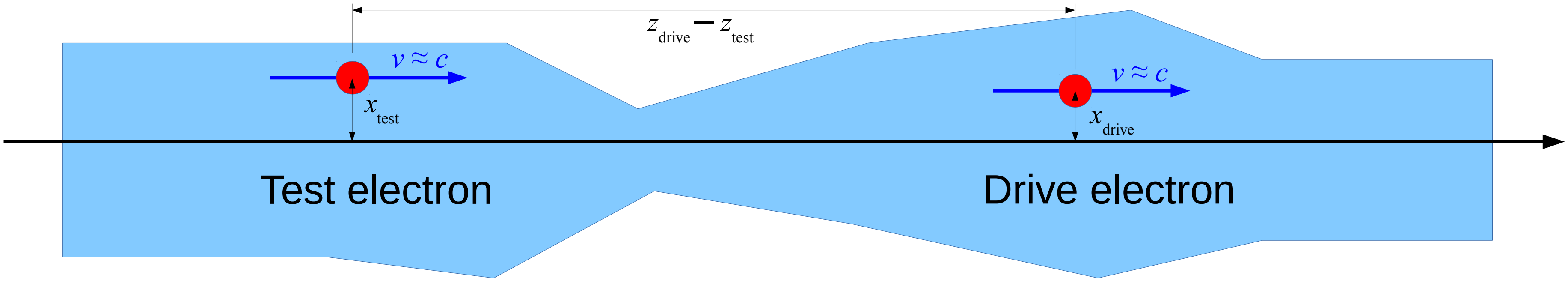

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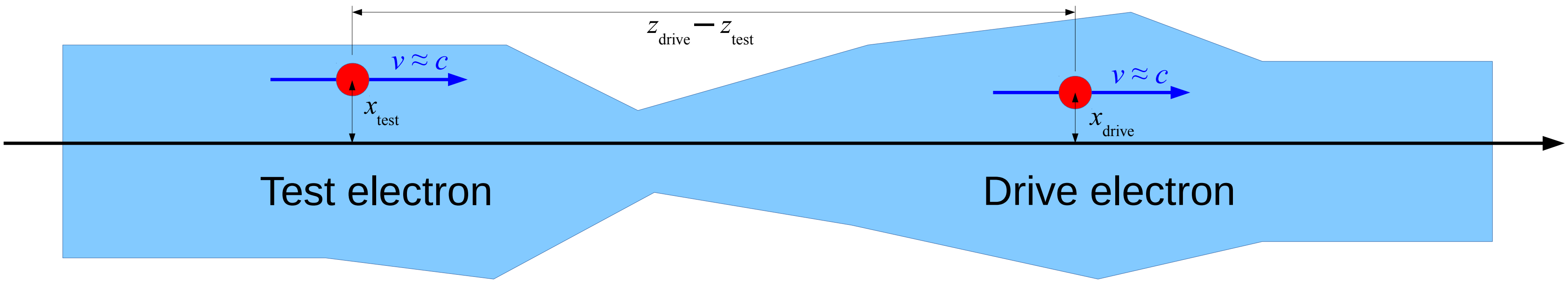

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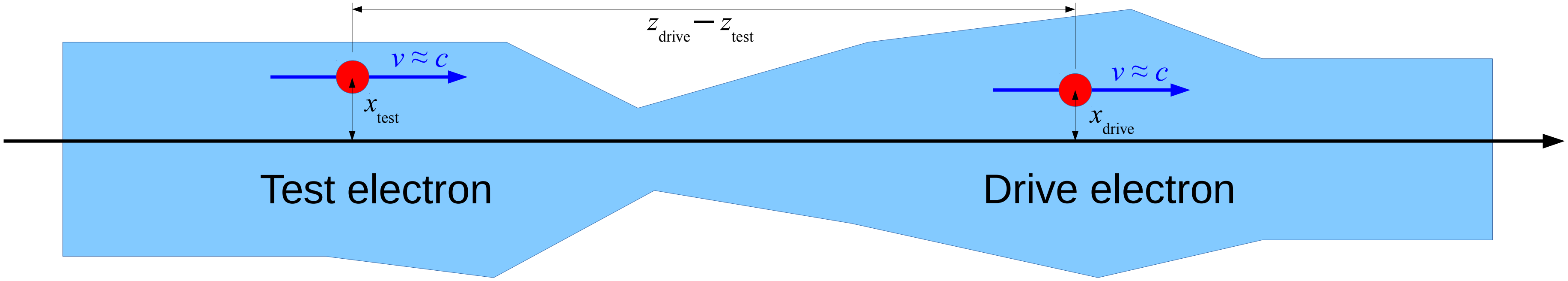

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Effect of "dipole" wakefield scales with displacement of drive electron; source of collective instabilities

Impedance is the Fourier transform of the wakefield with respect to $\tau = z_{\text{drive}} - z_{\text{test}}$:
$$Z_{x,D}(k) = \frac{i}{c}\int d\tau\; e^{-ik\tau}W_{x,D}(\tau)$$

Effects of transverse impedance on electron beam

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  - Examples: crotch absorber, anti-chambers, my initial design of the photon absorbers
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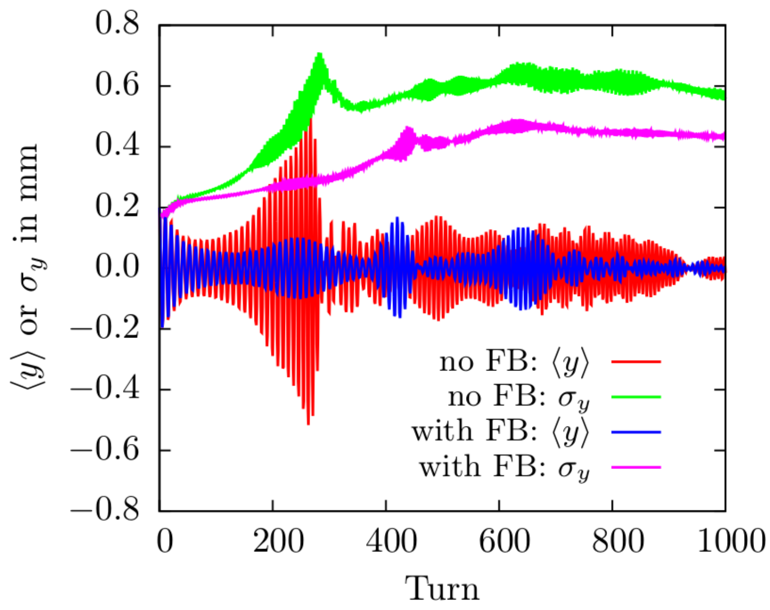

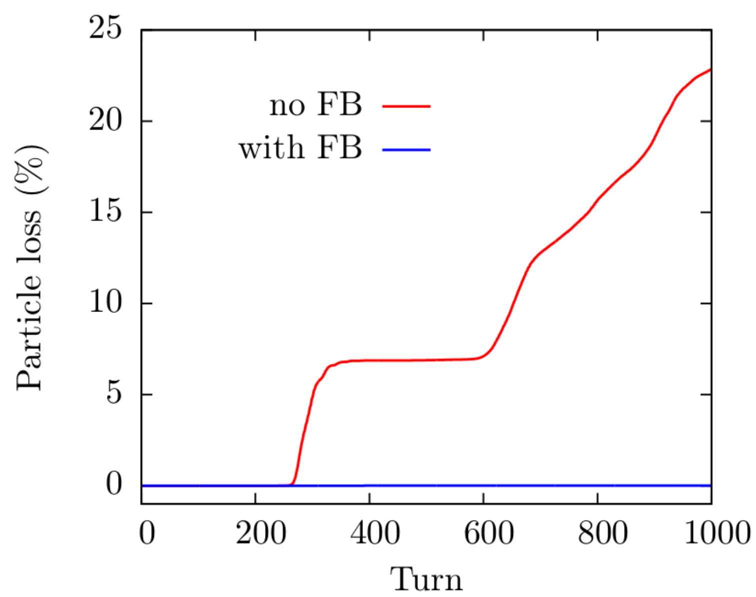

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- Hence, minimizing $Z_{||}(k)$ typically minimizes $\boldsymbol{Z}_\perp(k)$

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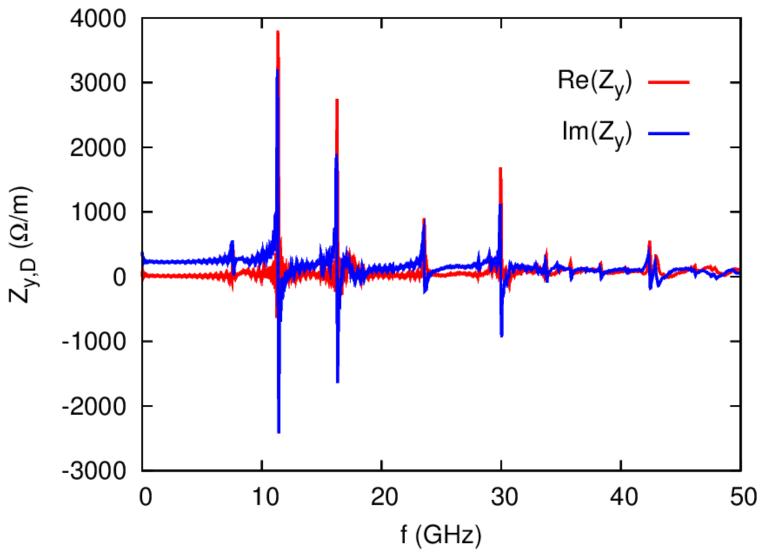
$$\boldsymbol{\nabla}_\perp Z_{||}(k, \boldsymbol{x}; \boldsymbol{x}_{\text{drive}}) = k\boldsymbol{Z}_\perp(k, \boldsymbol{x}, \boldsymbol{x}_{\text{drive}})$$

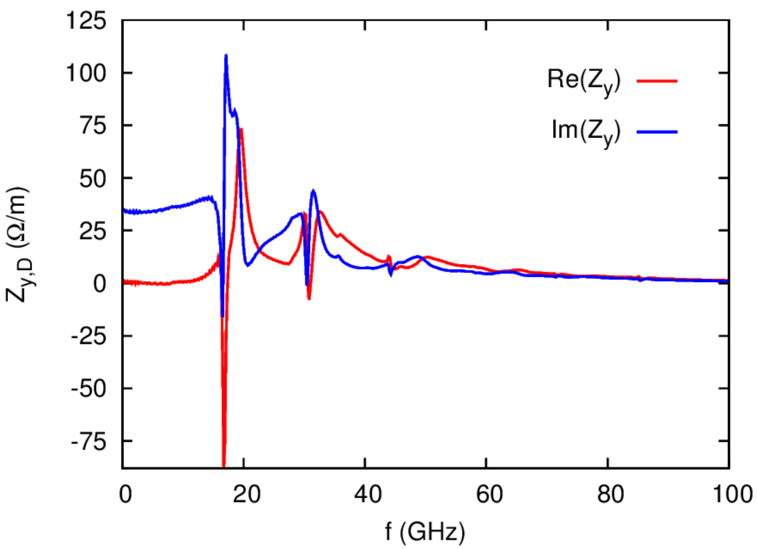
Also, we have

$$Z_{||}(k, \boldsymbol{x}; \boldsymbol{x}_{\text{drive}}) \approx Z_{||}(k, 0; 0) \quad \& \quad Z_x(k, \boldsymbol{x}, \boldsymbol{x}_{\text{drive}}) \approx Z_{x,M}(k) + x_{\text{drive}} Z_{x,D}(k) + x_{\text{test}} Z_{x,Q}(k)$$

$$\Rightarrow |\boldsymbol{Z}_{\perp,D}(k)| \sim \frac{1}{k}\frac{1}{b^2}\left|Z_{||}(k)\right|$$

- Hence, minimizing $Z_{||}(k)$ typically minimizes $\boldsymbol{Z}_\perp(k)$





Conclusions

- Accelerator design is a highly collaborative effort that involves many people having a wide range of technical expertise
- Managing the synchrotron radiation heat loads is an important part of vacuum design
- The impedance cost of vacuum components must be weighed when designing components (an ongoing process)
  - Longitudinal impedance lengthens the bunch and may increase its energy spread (microwave instability)
  - Longitudinal impedance also leads to rf heating that should be understood and controlled
  - Transverse impedance can drive collective instabilities that may lead to emittance growth or, more typically, beam loss
- Joe Calvey will now continue with more on vacuum and ion effects...