Resistive-wall impedance of interaction regions (warm beam pipe)[1][2]

Bernard Riemann

technische universität dortmund
Zentrum für Synchrotronstrahlung
CERN

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[1] thanks to S. Arsenyev, A. Langner, O. Boine-Frankenheim, D. Schulte and S. Khan

[2] supported by German Federal Ministry of Education and Research, funding code `05P15PERB1`

Transverse impedance model

Preface: Tune shift[a]

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[a] thanks to O. Boine-Frankenheim

Transverse tune shift,[a] proportionality

$$\Delta\nu_y = \frac{\Omega - \omega_\beta}{\omega_0} \propto \beta_y I \tilde{Z}_\perp / E.$$

Normalize such that $\beta_y(s) = 1$ case is equivalent to impedance $Z_\perp$ of harmonic oscillator with frequency

$$2\pi Q = \int \frac{1}{\beta(s)}\,\mathrm{d}s =: \frac{1}{\beta_{smooth}}.$$

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[a] A. Chao, "Physics of Collective Beam Instabilities in High Energy Accelerators", chapter 4

Transverse impedance model

- Use single-kick model[3] for elements n of a lattice:

$$Z_\perp = \frac{1}{\beta_\perp^{smooth}} \sum_n \beta_\perp(s_n) \tilde{Z}_{\perp,n}$$

- round pipe, radius b

$$\tilde{Z}_{\perp,n} = L_n \; Z_0 \delta_n^{\text{skin}} \frac{1+\mathrm{i}}{2\pi b_n^3} \text{ with } \delta_n^{\text{skin}} = \sqrt{\frac{2\rho_n}{\mu_0 \mu_r \omega}}$$

- elliptical pipe with semiaxes w, b: Use form factors $G_{1\perp}(w, b)$ [4][5]

$$\tilde{Z}_{\perp,n} = L_n \; G_{1\perp}(w_n, b_n) Z_0 \delta_{skin} \frac{1+\mathrm{i}}{2\pi b_n^3}$$

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[3] N. Mounet, PhD thesis, EPFL Lausanne (2012)

[4] R.L. Gluckstern, J. van Zeijts and B. Zotter, Phys. Rev. E **47** (1992)

[5] K. Yokoya, Part. Acc. **41** (1993), p. 18 – 19

Transverse impedance model

$$Z_\perp = \frac{Z_0}{\sqrt{2\mu_0\mu_r\omega}} \frac{1+\mathrm{i}}{\pi\beta_\perp^{smooth}} \sum_n L_n\, \beta_\perp(s_n) G_{1\perp}(w_n, b_n) \frac{\sqrt{\rho_n}}{b_n^3}$$

- assume $G_{1\perp}, \rho, b$ as piece-wise constant, but β as continous:

$$Z_\perp = \frac{Z_0}{\sqrt{2\mu_0\mu_r\omega}} \frac{1+\mathrm{i}}{\pi\beta_\perp^{smooth}} \sum_n G_{1\perp}(w_n, b_n) \frac{\sqrt{\rho_n}}{b_n^3} \int\limits_{s_{n-1}}^{s_n} \beta_\perp(s)\,\mathrm{d}s$$

- $\beta, \alpha = -\beta'/2$ known at all element endpoints s_n

Transverse impedance model

Quadrature rule

Assume β is piece-wise cubic function of s:

$$\int_0^L \beta(s)\,\mathrm{d}s \approx L\frac{\beta(L)+\beta(0)}{2} + L^2\frac{\alpha(L)-\alpha(0)}{6}.$$

- Approximation is exact for drift spaces (quadratic dependence).

Result

$$Z_\perp = \zeta\frac{1+\mathrm{i}}{\sqrt{f}}, \text{ with}$$

$$\zeta = \frac{Z_0}{2\pi\beta_\perp^{smooth}\sqrt{\pi\mu_0\mu_r}}\sum_n G_{1\perp}(w_n, b_n)\frac{\sqrt{\rho_n}}{b_n^3}\int_{s_{n-1}}^{s_n}\beta_\perp(s)\,\mathrm{d}s.$$

Longitudinal impedance model

- Different dependence on b and f,[6]
- assumption of piece-wise constant values is valid for all factors:

Result

$$Z_\perp = \alpha(1+\mathrm{i})\sqrt{f}, \text{ with}$$

$$\alpha = \frac{Z_0}{2\pi c}\sqrt{\frac{\pi}{\mu_0 \mu_r}} \sum_n L_n \frac{\sqrt{\rho_n}\, G_0(w_n, b_n)}{b_n}.$$

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[6] A. Chao, *Physics of Collective Instabilities in Particle Accelerators* (Wiley, 2003)

Computation results

- Used aperture and optics data from 8 IRs as input.[7]
- Collision optics with $\beta^* = 0.3\,\mathrm{m}$ at 50 TeV beam energy.
- Used resistivities of copper[8] at 50 K for magnets (elements `QUADRUPOLE`, `RBEND`, `SBEND`, `HKICKER`, `VKICKER`)

  $$\rho(50\,\mathrm{K}) = 0.518\,\mathrm{n\Omega\,m}$$

  respectively 293 K for drift spaces

  $$\rho(293\,\mathrm{K}) = 16.78\,\mathrm{n\Omega\,m}.$$

- other lattice elements ignored (no treatment of collimators etc.)

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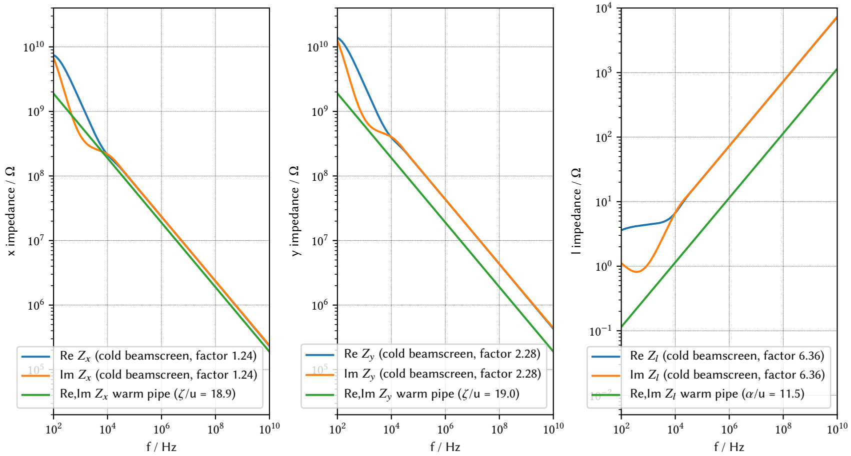
[7] thanks to S. Arsenyev and A. Langner

[8] R.A. Matula, "Electrical Resistivity of Copper, Gold, Palladium, and Silver", Table 2, J. Phys. Chem. Ref. Data **8** (4) (1979)

Total impedance regions A, B, D, F, G, H, J, L



Transverse plane: strong contribution
relative to cold beamscreen reference data.[9]

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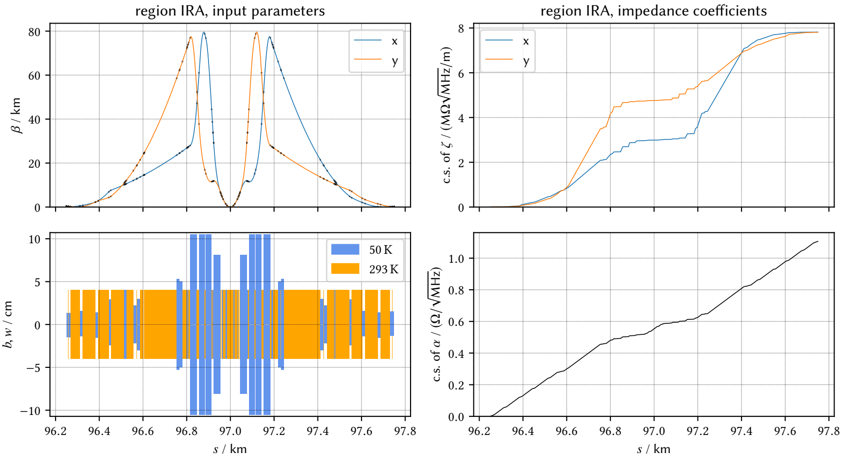
[9] S. Arsenyev, FCC impedance online database, `https://impedance.web.cern.ch/impedance/fcchh`

Major transverse contributions from IRA / IRG

IRA	ζ / (M$\Omega\sqrt{\text{MHz}}$/m)		
elements	x plane	y plane	α / ($\Omega/\sqrt{\text{MHz}}$)
drifts	7.190	7.118	1.007
quads	0.168	0.236	0.064
dipoles	0.379	0.372	0.024
kickers	0.082	0.080	0.010
total	7.818	7.806	1.106

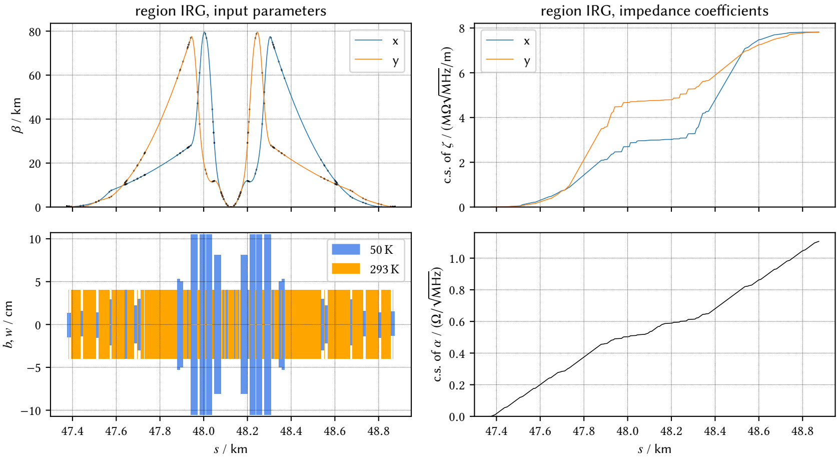


region IRA, input parameters

region IRA, impedance coefficients

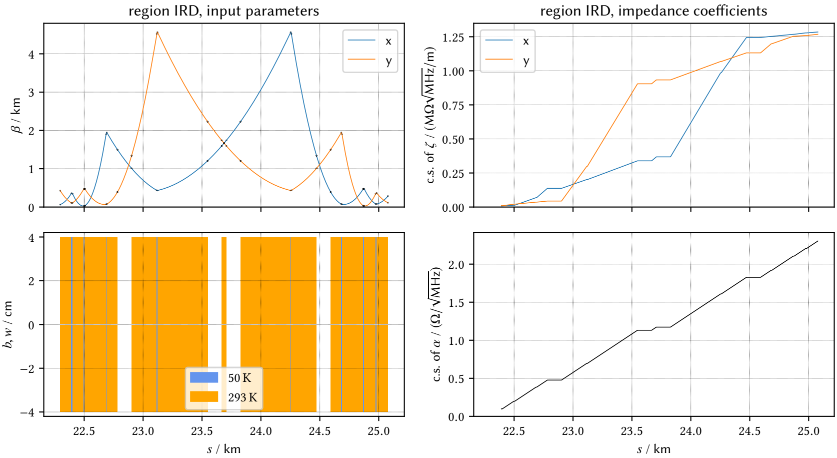
Major transverse contributions from IRA / IRG

IRG	ζ / (M$\Omega\sqrt{\text{MHz}}$/m)		
elements	x plane	y plane	α / ($\Omega/\sqrt{\text{MHz}}$)
drifts	7.190	7.118	1.007
quads	0.168	0.236	0.064
dipoles	0.379	0.372	0.024
kickers	0.082	0.080	0.010
total	7.818	7.806	1.106



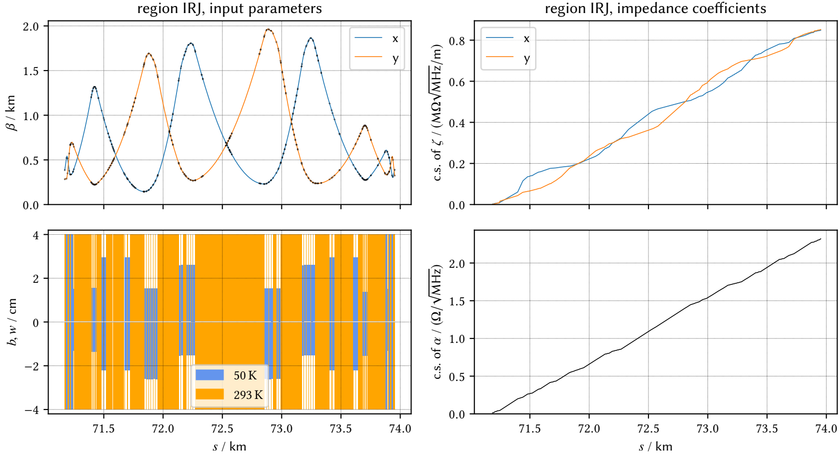
Minor transverse contributions from IRD, IRJ

IRD	ζ / (M$\Omega\sqrt{\text{MHz}}$/m)		
elements	x plane	y plane	α / ($\Omega/\sqrt{\text{MHz}}$)
drifts	1.281	1.264	2.292
quads	0.004	0.004	0.011
dipoles	0.000	0.000	0.000
kickers	0.000	0.000	0.000
total	1.285	1.268	2.304



Minor transverse contributions from IRD, IRJ

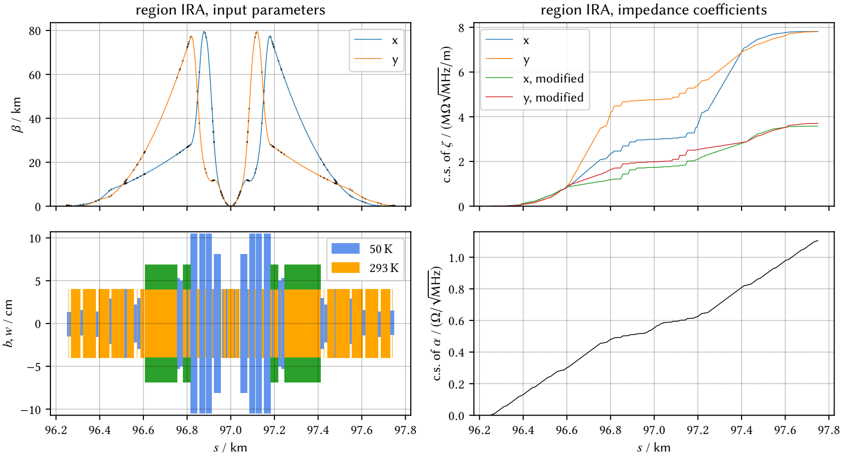
IRJ	ζ / (M$\Omega\sqrt{\text{MHz}}$/m)		
elements	x plane	y plane	α / ($\Omega/\sqrt{\text{MHz}}$)
drifts	0.659	0.647	2.104
quads	0.179	0.175	0.186
dipoles	0.010	0.030	0.031
kickers	0.000	0.000	0.000
total	0.848	0.852	2.321



region IRJ, input parameters

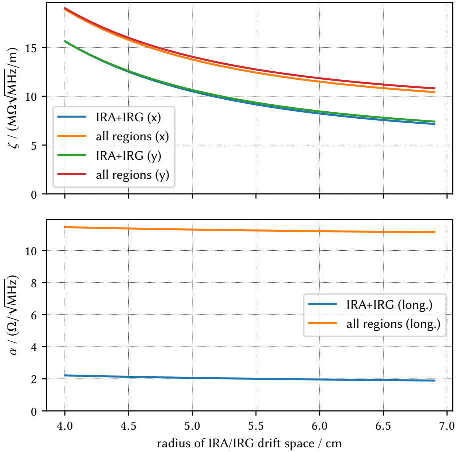
region IRJ, impedance coefficients

Influence of IR apertures in IRA / IRG



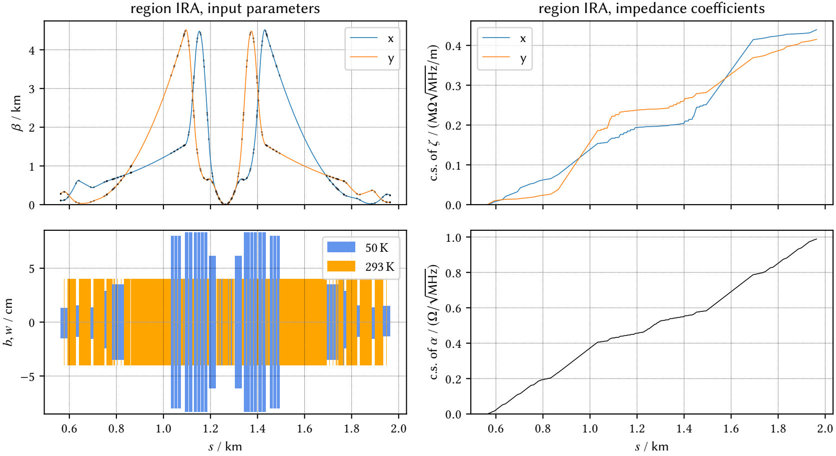
- Strong influence by scaling law $\propto \sqrt{\rho}\beta/b^3$ from high-beta drift spaces.

Influence of IR apertures in IRA / IRG



- Significant reduction of transverse impedance possible by enlarging the aforementioned apertures.

Sneak peek: Injection optics



⟹ Current task: repeat computation for 3.3 TeV injection optics.

- factor 20 in β, Z values

Summary

- Transverse and longitudinal resistive-wall impedance contributions of major warm parts have been computed for collision optics at 50 TeV with $\beta^* = 0.3\,\mathrm{m}$.
- Overall impedance of warm parts is of approx. equal magnitude to that of cold beamscreen.
- Major contributions from room-temperature drift spaces in IRA / IRG, which can be removed by aperture increase.

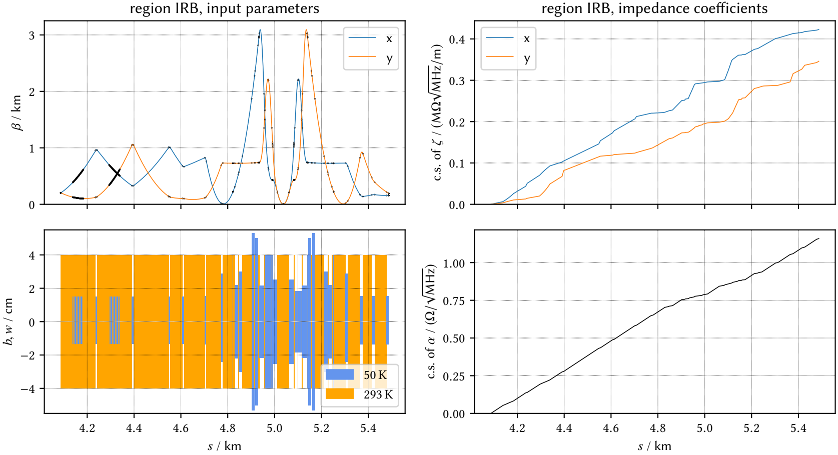
Next tasks

⇒ Re-evaluate computation with modified aperture dimensions (further input welcome)

Thank you for your attention!

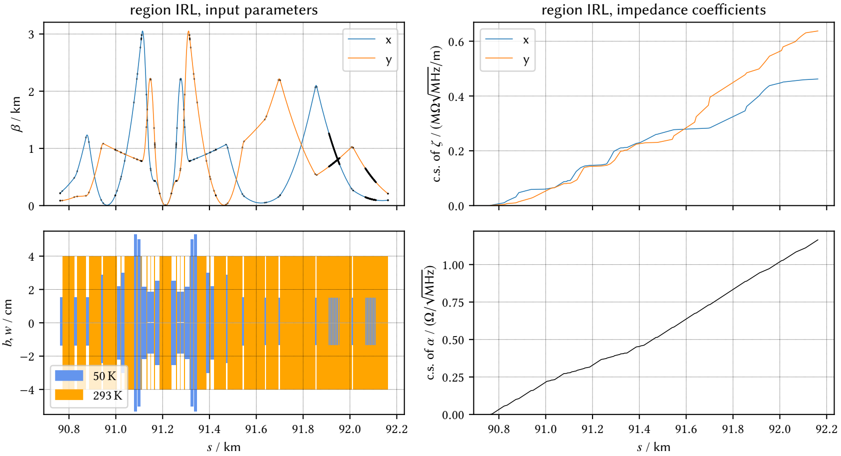
Backup slides IRB

IRB	ζ / (M$\Omega\sqrt{\text{MHz}}$/m)		
elements	x plane	y plane	α / ($\Omega/\sqrt{\text{MHz}}$)
drifts	0.252	0.184	1.033
quads	0.121	0.115	0.075
dipoles	0.015	0.014	0.024
kickers	0.035	0.033	0.027
total	0.423	0.346	1.159



Backup slides IRL

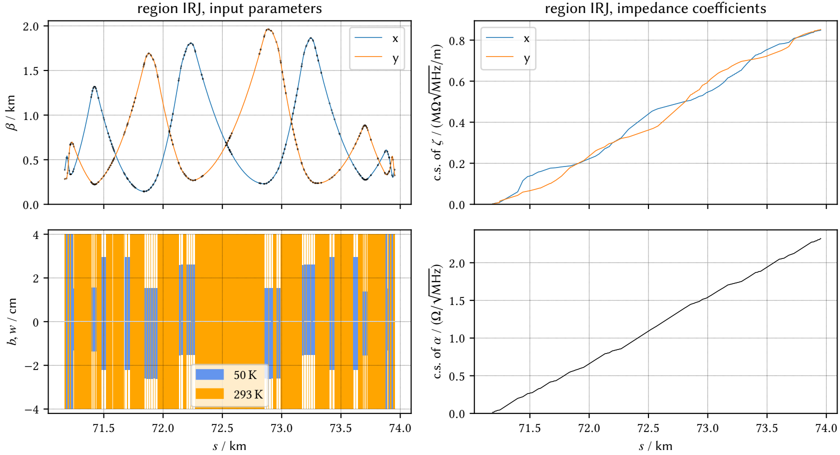
IRL	ζ / (M$\Omega\sqrt{\text{MHz}}$/m)		
elements	x plane	y plane	α / ($\Omega/\sqrt{\text{MHz}}$)
drifts	0.264	0.357	1.033
quads	0.147	0.193	0.081
dipoles	0.016	0.016	0.024
kickers	0.035	0.071	0.027
total	0.462	0.637	1.165


region IRL, input parameters

region IRL, impedance coefficients

Backup slides IRJ

IRJ	ζ / (M$\Omega\sqrt{\text{MHz}}$/m)		
elements	x plane	y plane	α / ($\Omega/\sqrt{\text{MHz}}$)
drifts	0.659	0.647	2.104
quads	0.179	0.175	0.186
dipoles	0.010	0.030	0.031
kickers	0.000	0.000	0.000
total	0.848	0.852	2.321



Backup slides IRH

IRH	ζ / (M$\Omega\sqrt{\text{MHz}}$/m)		
elements	x plane	y plane	α / ($\Omega/\sqrt{\text{MHz}}$)
drifts	0.101	0.108	1.214
quads	0.011	0.018	0.026
dipoles	0.001	0.002	0.018
kickers	0.000	0.000	0.000
total	0.113	0.128	1.258