Overview of Impedance in Electron/Positron Machines

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SOLEIL SYNCHROTRON

CLIC

◊ Two Types of Lepton Machines: High *E* physics and Light Source (LS) rings

- A long history of high *E* physics (e-/e+) rings since ~1950s (ADA, ADONE, ACO, VEPP, SPEAR, …).

- Later (since 1970s) appeared LSs (KEK-PF, SRS, SuperACO,…). Above all, a large number of them were built since ~1990s as 3rd Generation LSs.

- Common aspect between the two types of machines: High current operation (high luminosity and high brilliance).

- Optimisation of LSs nevertheless render them distinct from the former: Use of low emittance beam and low gap Insertion Devices (IDs).

- Recent damping rings for high *E* physics experiments require low emittance beams as well.

- The vacuum chamber structures, namely the coupling impedance, may differ significantly in general between the respective machines.

◊ Impedance Characteristics for High *E* Physics Lepton Machines

- Main impedance contributors:
  - Cavities (HOMs and broadband)
  - Kickers and striplines
  - Ion clearing electrodes
  - Interaction Point region chambers
  - Flanges/BPMs/bellows/RF masks/pumping holes (existing in large numbers), …
  - Electron-clouds (for e+)/Fast-ions (for e-)

- Many of these components were studied analytically and found to be mostly inductive at low frequencies (where the beam interacts most importantly).

- Numerical studies made with *TBCI*,*URMEL*, *ABCI*, *MAFIA*, …

- Efforts to minimise the impedance led to the inventions of RF masks, fingers, shielded bellows, optimised pumping hole shapes, tapers, …

- Formation of electron clouds is suppressed with TiN coated chambers

ex) Impedance estimate for KEKB:

taken from "Impedance estimation of SuperKEKB components ", S. Stanic, KEK, February 2003

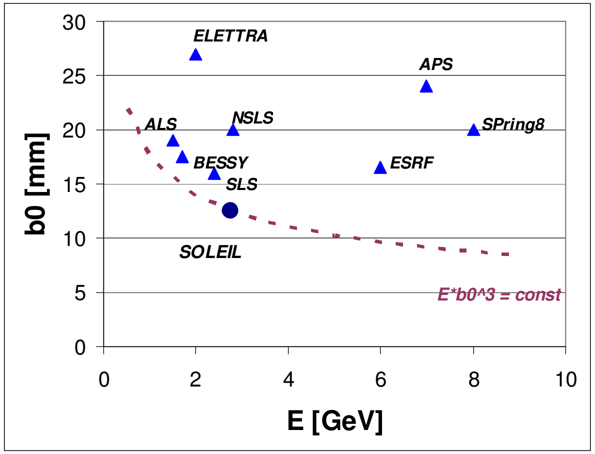
KEKB LER σ=4mm	No. of items	Loss factor [V/pC]
ARES cavity	20	10.6
SC cavity	-	-
Resistive wall	3016m	4.0
Masks at arc	1000	4.6
Pumping slots (arc)	10×1800	0.37
Pumping slots (straight)	800	+
BPMs	4×400	0.79
Masks at IP	1	0.08
IP chamber	1	0.29
Recomb. chambers	2	1.6
Bellows	1000	2.5
Flange gap	2000	+
Trans. to antechamber	-	-
Gate valve	40	+
Feedback kicker	1	+
Inj./abort kickers	4	+
Septum	1	+
Movable masks	16	+
HOM absorbers (RF end)	4	+
Tapers (RF end)	4	+
Total		25.7+

- Relative contribution of the resistive-wall impedance may be said to be small in many existing machines (especially as compared to recently built LSs)

- Future high *E* physics lepton machines generally involve shorter bunches
  → Enhanced importance of high frequency impedance

◊ Impedance Characteristics for 3rd GLS Machines

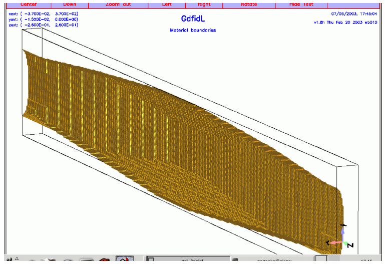
- Low gap chambers for Insertion Devices (IDs) and small bore magnets for stronger focusing
  → Smaller effective chamber radius b_{eff}
  → Distributed impedance.



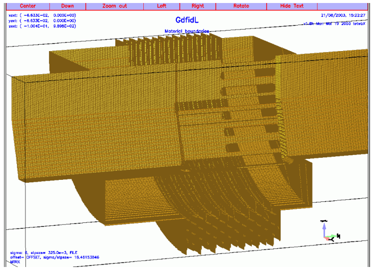
Vertical half aperture of the standard chamber versus machine energy in several light source storage rings

- Main contributors of impedance:

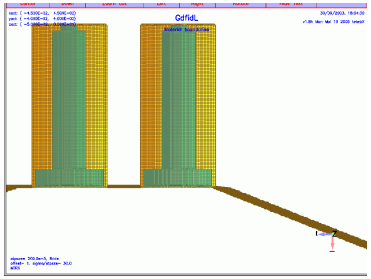
  - Resistive-wall of vertically narrow gap chambers
  - 3D flat chamber tapers
  - Flanges/BPMs/bellows (existing in large numbers)
  - Localised impedance: Scrapers/cavities/kickers/ceramic chambers/roughness



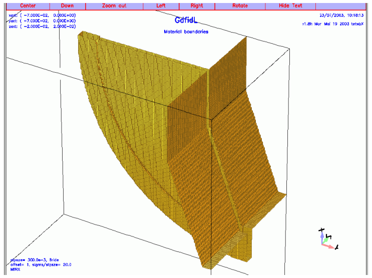
taper



bellows



BPM

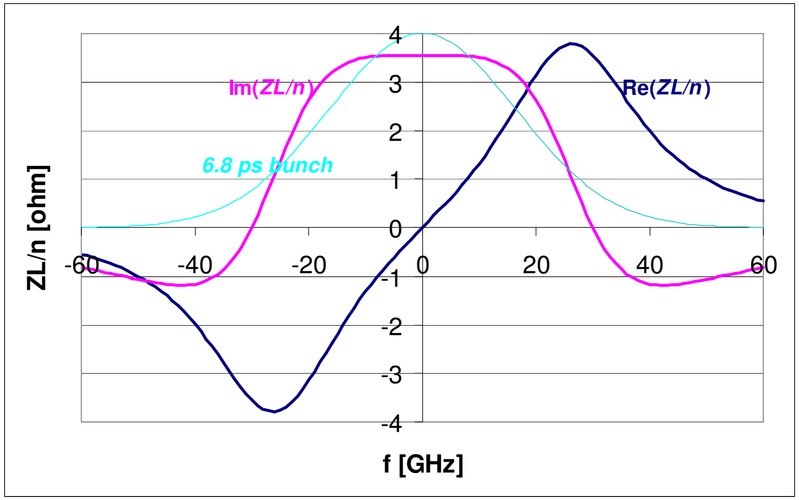


flange

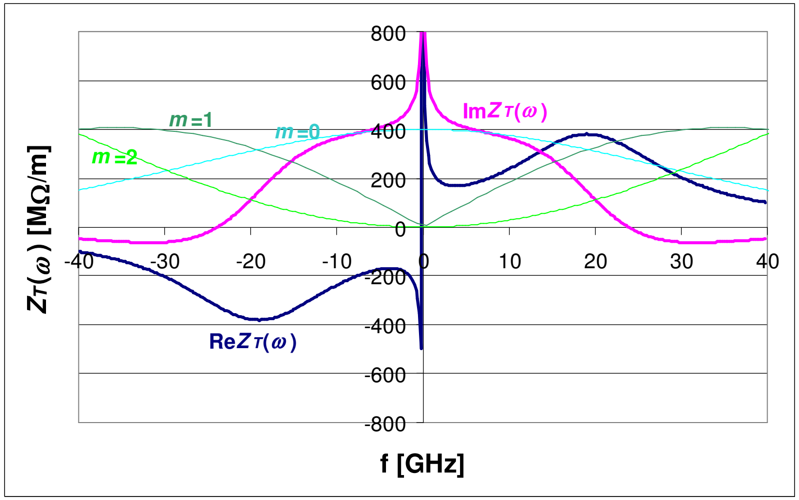
- Typical overall impedance:

- Large inductive and narrow resistive-wall at low frequencies.

- Enhanced resistive components creating a broad resonance at high (~tens of GHz) frequencies, often associated with resonant (trapped) modes.



Longitudinal



Vertical

- In addition to the codes mentioned, *GdfidL* and *HFSS* are used in several LSs

- Many of the recently built LS rings estimate $|Z/n|_{eff}$ to be few tenths of an ohm.

◊ Impact of the Described Impedance on Beam Instability

- Cavity-like high *Q* resonances create coupled-bunch instabilities.
- Most of the impedance contributors have large inductive components at low frequencies. They induce bunch lengthening and coherent tune shifts.
- Many contributors have resistive components at high frequencies. They are responsible for the single bunch microwave and headtail instabilities.
- Low resistive-wall instability threshold may be overcome with positive chromaticity. However, the beam may become unstable due to excitation of higher-order headtail modes interacting with the broadband impedance.
- In a machine with low gap and non-circular chambers, current-dependent incoherent tune shifts (and therefore, the optics distortion) may become non-negligible.
- Taper sections with high horizontal betas may create significant coupling effects lowering the horizontal thresholds (as observed in several LSs).

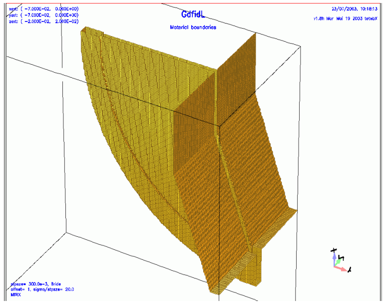
◊ Studies of Impedance and its Minimisation

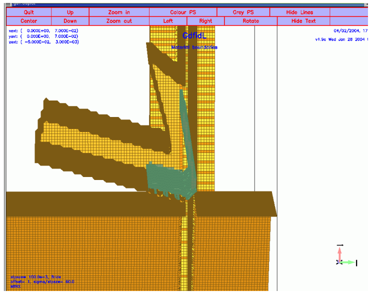
- Analytical works (resistive-wall, tapers, roughness, high frequency wakes, CSR,…)

- Numerical/analytical evaluation and remodelling of vacuum components

SOLEIL examples:

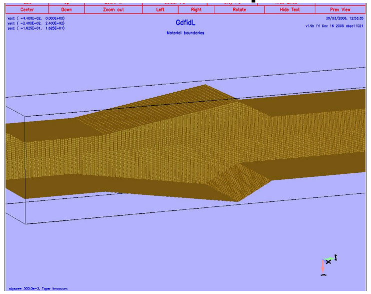
• Unshielded/shielded flanges



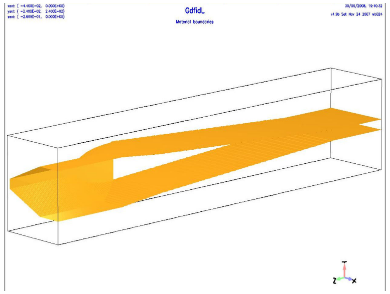


	(Power)500 mA [kW]	Σ (*ZL/n*)*eff* [Ω]	Σ *βV**(Im*ZV*)*eff* [MΩ]
Original	6.0	0.37	1.04
Short-circuited	0.1	0.01	0.04
Ratio	**54.6**	**37.0**	**26.0**

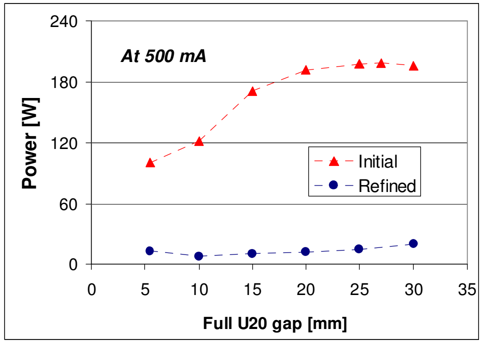
• In-vacuum ID tapers



Initial model



Refined model



- Importance of beam-based impedance measurements

◊ Impact of Low Emittance on the Beam Interaction with the Impedance

Small horizontal dispersion → Small momentum compaction $\alpha = \frac{1}{L_c}\oint \frac{\eta}{\rho_0}\, ds$

→ Shorter natural bunch length $\sigma_\tau = \sqrt{\frac{\alpha R}{J_\varepsilon \rho_0}\frac{2\pi C_q}{(mc^2)^2}\frac{E^3}{e\omega_{rf}V_{rf}\cos\varphi_s}}$

→ Wider bunch and headtail spectra

→ Smaller synchrotron tune $Q_s = \sqrt{\frac{\alpha h V_{rf}\cos\varphi_s}{2\pi E\ /e}}$

→ Enhanced sensitivity against single bunch instabilities, such as,

- *Mode detuning and TMCI*

$$\frac{df_\beta}{dI} = -\frac{\beta}{8\pi^{3/2}\sigma_\tau E/e}\cdot \mathrm{Im}(Z_T)_{eff}$$

- *Microwave instability*

$$I_{th} = \frac{1.5\omega_0^3\cdot\sigma(I_{th})^3\cdot V_{rf}h\,|\cos\varphi_s|}{\frac{R_{eff}}{p_r}\sqrt{2\pi}}$$

- Lowering the emittance with a larger machine circumference may enhance RW instability (*NB*: *Anomalous resistive-wall impedance found at CERN*)

$$\tau^{-1} = \frac{\beta\omega_0 I}{4\pi E/e}\cdot\frac{R}{b_{eff}^{\ 3}}\sqrt{\frac{2\rho}{(1-\Delta Q_\beta)\omega_0\varepsilon_0}}$$

cf) Enhanced sensitivity of short bunch & low emittance beam to impedance
K. Bane, EPAC 2004

◊ Summary

- The impedance content may differ considerably between high *E* physics lepton machines and LSs, due to distinct vacuum chamber structures.
- The impedance of many of the vacuum components are understood to be inductive at low frequencies.
- The wide spectrum nature of the low emittance e/e+ beams requires good knowledge of high frequency impedance, which are not necessarily inductive and must be studied further both theoretically and numerically, for both types of machines.
- The combination of short low emittance bunches and narrow gap vacuum chambers demands special care to minimise the coupling impedance for tapers and structures that could excite trapped modes.
- For machines requiring high current operations, care to reduce the beam-induced heating of vacuum chambers would be especially important.