Photon Stoppers & Resistive Wall

Some First Results

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138th F.C.C.-ee Optics Design Meeting
&
9th F.C.C.I.S. W.P.2.2 Meeting

FUTURE
CIRCULAR
COLLIDER

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Purpose of this Study

- An idea was presented on the 132^{nd} F.C.C.-ee Optics Design Meeting to nest the arc quads and sextupoles and make them superconducting.
- One of the questions raised is how much would this idea increase the **resistive wall impedance** budget (and, therefore, wasted power) of the machine.
- This idea accommodates much smaller winglets than the C.D.R. [2] design (i.e. 110mm $\rightarrow$ 86mm) for the length of the S.S.S. (i.e. $3.4m$).
- It also calls for **photon stoppers** that possibly protrude more into the beam pipe than the C.D.R. [2] design.
- This is a preliminary study for a quick comparison between options and not a substitute for an in-depth analysis by the experts.

Coupling Impedance & Loss Factor

Theoretical Formulas

Longitudinal Impedance [Ω] & Transverse Dipole Impedance [$\frac{\Omega}{m}$]

$$Z_{\parallel}(\omega) := \frac{1}{c}\int_{-\infty}^{\infty} w_{\parallel}(z)e^{i\frac{\omega z}{c}}dz \tag{1}$$

$$Z_{\perp}(\omega) := -\frac{i}{c}\int_{-\infty}^{\infty} w_{\perp}(z)e^{i\frac{\omega z}{c}}dz \tag{2}$$

Loss Factor [$\frac{V}{C}$]

$$k = -\frac{U(z=0)}{q^2} \xrightarrow{\text{B.L.T.}} k = \frac{w_{\parallel}(z \to 0)}{2}$$

Wake Potential & Energy Loss of Bunched Distribution

Theory

$$dU(z) = -ew_{\|}(z'-z)dq(z') = -ew_{\|}(z'-z)\lambda(z')dz'$$

Energy lost by e due to a thin slice (dz') of the distribution

$$U(z) = -e\int_{z}^{\infty} w_{\|}(z'-z)\lambda(z')dz'$$

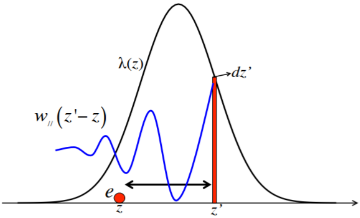
Energy lost by e due to the whole distribution

$$q = \int_{-\infty}^{\infty}\lambda(z)dz$$

Total distribution charge

$$W_{\|}(z) = -\frac{U(z)}{qe} = \frac{1}{q}\int_{-\infty}^{\infty} w_{\|}(z'-z)\lambda(z')dz'$$

Longitudinal wake potential of a distribution



Source: [1]

Loss Factor of Gaussian Bunch

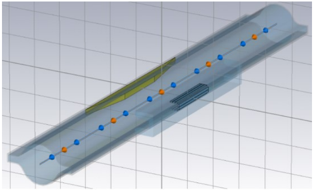
Analytical Formula for Circular Pipe

Loss Factor of Gaussian Bunch in Circular Copper Beam Pipe $[\frac{V}{C}]$

$$\frac{k_{\parallel}}{L} = \frac{\Gamma(\frac{3}{4})c}{4\pi^2 r\sqrt{\sigma_z^3}}\sqrt{\frac{Z_0}{2\sigma_c}} \tag{3}$$

- $\Gamma(\frac{3}{4}) \approx 1.225$
- $c \approx 3 \times 10^8 \frac{m}{s}$
- $\sigma_c \approx 6 \times 10^7 \frac{S}{m}$
- $r =$ Beam pipe radius
- $\sigma_z =$ Gaussian bunch length
- $Z_0 =$ Impedance of free space $\approx 377\ \Omega$

C.D.R. Recap



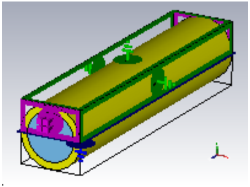
3D model of the F.C.C.-ee chamber and a S.R. absorber with pumping slots used for C.S.T. simulations. (source: [2])

Beam pipe radius (r)	$= 35mm$
Winglet total width (X)	$= 110mm$
Winglet height (Y)	$= 11mm$
Photon stopper length	$\approx 300mm$

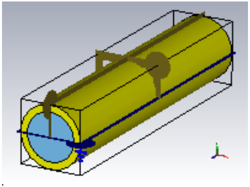
- Photon incident angle is $2.55mrad$
- $1m$ of longitudinal S.R. spreads over $2.5mm$ transversely at the stopper
- Half cell length is $27.9m$
- If we use 5 stoppers per half cell, the average distance between stoppers is 5.6 m and each stopper would need to be 14.3mm thick
- Stopper size and distance might vary in this new approach

A Priori Assumptions

- Materials used $\begin{cases} \text{pure copper}, & \sigma_c = 5.96 \times 10^7 \frac{S}{m} \\ \text{customised ``copper''}, & \sigma_c = 5.96 \times 10^3 \frac{S}{m} \end{cases}$
- Particle beam $\begin{cases} \text{beam shape} & = \text{Gaussian} \\ \sigma_{beam} & = 12.1mm \end{cases}$
- Conditions $\begin{cases} \text{boundary} & : X\&Y \rightarrow E_t = 0 \text{ and } Z \rightarrow \text{open} \\ \text{symmetry} & : XY\&YZ \rightarrow \text{none and } XZ \rightarrow H_t = 0 \end{cases}$



Boundaries (electric)

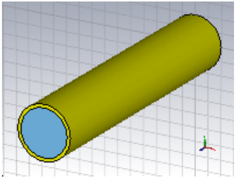


Symmetry planes (magnetic)

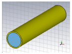
Cylindrical Copper Pipe

- Many thanks to Mauro Migliorati for providing guidance with C.S.T. Studio.
- As a first consistency check we simulate the case of a round copper pipe and check the result against the theoretical value obtained by equation (3).
- For a 400mm long copper pipe of 35mm radius and 10mm thickness we are in good agreement with the analytical loss factor derived by (3), with approximately 4% relative error.

Values in $[\frac{V}{pC}]$	
Simulated	**Theoretical**
1.3705e-04	1.4215e-04

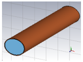


Cylindrical Pipe Comparative Table

Pipe Type		Geometry	Material	Length	σ_{beam}	Wakelength	Beam Direction	Loss Factor (k)	Analytical Loss Factor
				[mm]			+ or −	$[\frac{V}{pC}]$	
Cylindrical	 Plain	$r = 35mm$ $\delta = 100\mu m$	Cu	400	12.1	2000	+	0.7463e-04	1.4215e-04
			Cu×e-04					0.9525e-02	1.4215e-02
		−//− $\delta = 1mm$	Cu					1.3681e-04	1.4215e-04
			Cu×e-04					1.2990e-02	1.4215e-02
		−//− $\delta = 5mm$	Cu					1.3704e-04	1.4215e-04
			Cu×e-04					1.4379e-02	1.4215e-02
		−//− $\delta = 10mm$	Cu					1.3705e-04	1.4215e-04
			Cu×e-04					1.4379e-02	1.4215e-02

Elliptical Pipe Comparative Table I

Vacuum Chamber Area Invariant

Pipe Type		Geometry	Material	Length	σ_{beam}	Wakelength	Beam Direction	Loss Factor (k)
				[mm]			+ or −	$[\frac{V}{pC}]$
Elliptical	 Plain	$a = 41.41mm$ $b = 29.58mm$ (Area Invariant) $\delta = 100\mu m$	Cu	400	12.1	2000	+	0.8837e-04
		−//− $\delta = 1mm$						1.5343e-04
		−//− $\delta = 5mm$						1.5418e-04
		−//− $\delta = 10mm$						1.5418e-04

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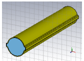
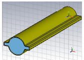
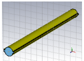
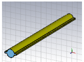
Cylindrical Pipe Variations Comparative Table I

Pipe Type		Geometry	Material	Length	σ_{beam}	Wakelength	Beam Direction	Loss Factor (k)
				[mm]			+ or −	$[\frac{V}{pC}]$
	 Short Winglets	$r = 35mm$ $X = 85mm$ $\delta = 2mm$		400		2000		1.4735e-04
	 Long Winglets	$r = 35mm$ $X = 110mm$ $\delta = 2mm$						1.4849e-04
Cylindrical	 Short Winglets & Cooling Pipe	$r = 35mm$ $X = 86mm$ $\delta = 2mm$	Cu	1000	12.1	5000	+	3.6790e-04
	 Long Winglets & Cooling Pipe	$r = 35mm$ $X = 110mm$ $\delta = 2mm$						3.6869e-04

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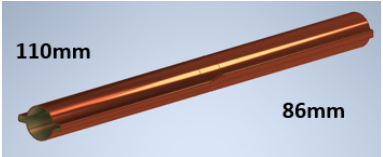
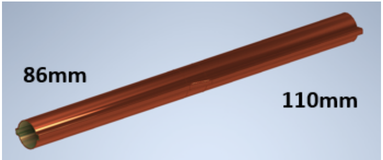
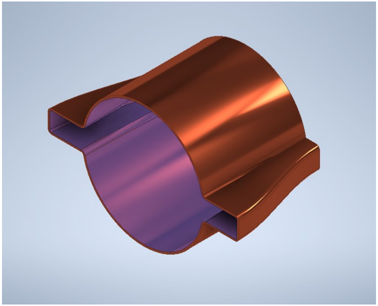
Beam Pipe Transitions



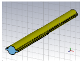
A smooth transition between a 110mm winglet to a 86mm winglet was developed (credits to my supervisor for this design).





Cylindrical Pipe Variations Comparative Table II

Transitional Beam Pipe

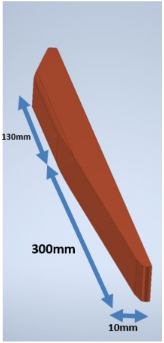
Pipe Type		Geometry	Material	Length	σ_{beam}	Wakelength	Beam Direction	Loss Factor (k)
				[mm]			$+$ or $-$	$[\frac{V}{pC}]$
Cylindrical	 Transitional	$r = 35mm$ $X_{small} = 86mm$ $X_{big} = 110mm$ $\delta = 2mm$	Cu	1000	12.1	5000	$+$	5.1243e-04
							$-$	4.3988e-04

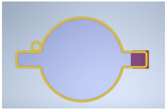
The difference between the $+z$ and $-z$ directions for the loss factor of the particle beam can be justified. According to [2] the impedance is mostly **resistive** when a particle exits into a beam pipe of greater radius.

Beam Pipe Geometry & Stopper Modifications

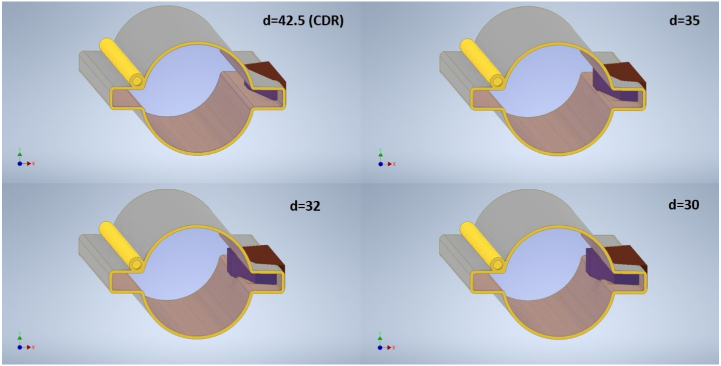
Modifications with respect to the C.D.R. stopper:

- Stopper is thicker.
- Stopper is longer.
- Cooling pipe addition.
- Stopper has photon incident slope of $\arctan(\frac{1}{30})$.
- Keeping the heat load less than $100W$ per cm.
- If this stopper receives 2.5 kW from 5m of S.R. power, then every cm receives a S.R. power of $83W$ in this specific example.





Variations of Stopper Geometries

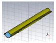


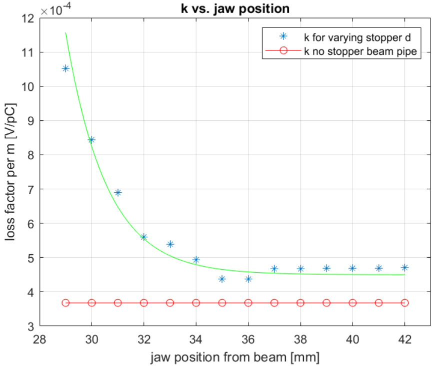
d is the distance (in mm) from the particle beam

Effect on **impedance** of different **stopper** protrusions could be determined through simulations over the variable stopper geometries.

Cylindrical Pipe Variations Comparative Table III

Beam Pipe with Stopper Variations & Cooling Pipe

Pipe Type		Geometry	Material	Length	σ_{beam}	Wakelength	Beam Direction	Loss Factor (k)
				[mm]			+ or −	$[\frac{V}{pC}]$
Cylindrical		$r = 35mm$ $X = 110mm$ $\delta = 2mm$ $d = 42mm$	Cu	1000	12.1	5000	−	4.7028e-04
		−//− $d = 40mm$						4.6898e-04
		−//− $d = 38mm$						4.6764e-04
		−//− $d = 36mm$						4.3686e-04
		−//− $d = 34mm$						4.9423e-04
		−//− $d = 32mm$						5.6078e-04
		−//− $d = 30mm$						8.4442e-04



Formula for Power Consumption Estimation

One can transform the equation by which the loss factor k is defined, in order to acquire an equation for the power consumption per beam, i.e.

$$\underbrace{P}_{\text{power consumption}} = n_{\text{bunches}} \times \left(n_{\frac{\text{particles}}{\text{bunch}}} \times e\right)^2 \times \underbrace{k}_{\text{loss factor}} \times \underbrace{f}_{\text{revolution frequency}}$$

Power Consumption Table

All Beam Pipe Types are 1m Long

Pipe Type	k	No. of Units	Total k	Total Power	C.D.R.		Premium
					k	Total Power	
	$[\frac{V}{pC}]$	[m]	$[\frac{V}{pC}]$	[MW]	$[\frac{V}{pC}]$	[MW]	
Beam pipe with 110mm winglet & cooling	3.69e-04	83250	30.72	2.32	3.69e-04	2.32	0.00
Beam pipe with ($d = 32mm$) stopper & cooling	5.61e-04	2900	1.63	0.12	4.70e-04†	0.10	0.02
Beam pipe with 110mm to 86mm transition & cooling	4.40e-04	2900	1.28	0.10	3.69e-04	0.08	0.02
S.S.S. pipe with 86mm winglet & cooling	3.68e-04	5800	2.13	0.16	3.69e-04	0.16	0.00
Beam pipe with 86mm to 110mm transition & cooling	5.12e-04	2900	1.48	0.11	3.69e-04	0.08	0.03
Sum	-	97750	-	2.81	-	2.74	0.07

Comments & Observations

- This exercise is not for giving definitive answers and the results are preliminary.
- Questions being tackled:
  - How much does the stopper cost in terms of R.W. power?
  - How much does a transition from wide to narrow winglet cost?
- An estimation of the increased overall power consumption has shown that the cost in terms of power is reasonable for this new proposal.

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