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STUDY OF A HORN WITH INTEGRATED TARGET FOR A NEUTRINO FACTORY

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1. Introduction

Preliminary technical studies are presented here to assess the feasibility of a triangular shaped horn as presented in [1].
The main design parameters considered are :
Maximum current : 300 kA to 400 kA
Repetition rate : 50 Hz
Waist radius : as close as possible to 25 mm
Many horns providing this peak current have already been built [2], [3], [4], but now there is the very high repetition rate and consequent higher heating problems. The demand on fatigue life time of 2 x 10^8 pulses is in addition to two orders of higher magnitude.

2. Reminder of the basic circuit

The current pulse for the production of the magnetic field is generated by the familiar oscillatory discharge of a capacitor bank C into the horn (inductance L and resistance R) as shown in Figure 1. The circuit is critically under-dampened i. e. $R^2 - 4\,L/C < 0$.

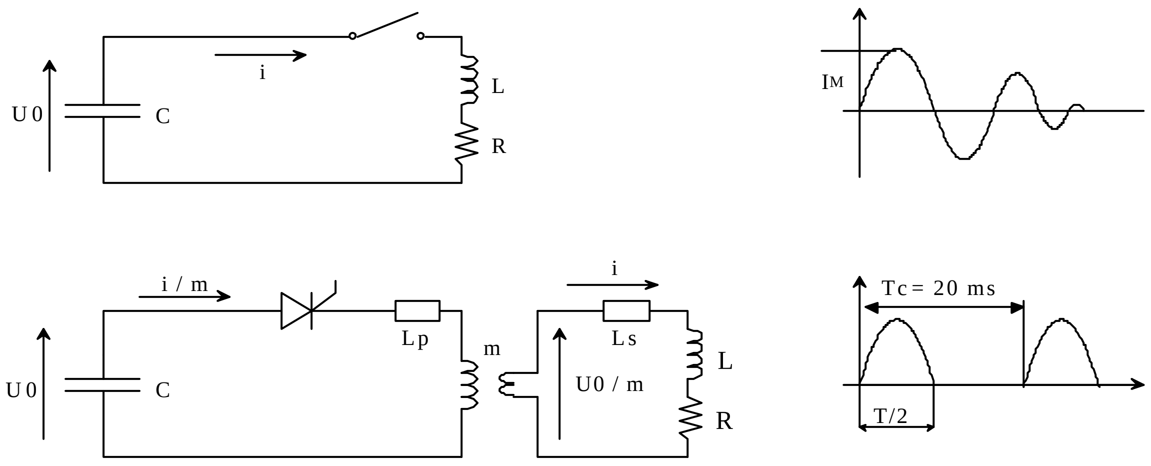

Figure 1: basic circuit

$i = (U_0/\omega L)\exp(-\delta t)\sin\omega t$

with $\delta = R/2L$

$\omega = \omega_0 \sqrt{(1-\gamma^2)}$

$\omega_0 = 1/\sqrt{(LC)}$

$\gamma = (R/2)\sqrt{C/L}$

U_0 is the charging voltage of the capacitor bank.

A pulse transformer of ratio m may be inserted close to the horn . It is advantageous

- if the capacitor bank is located far away, and so reduces losses in the two long primary power cables
- or to avoid switching to too high a current.

It is also a useful alternative if the aim is to work with low voltage on the horn ; this is indeed the case, particularly in very high radiation areas when one wants to avoid organic insulation.

3. A Horn with a transformer ?

The requested main parameters lead to very high Joule losses in the waist region. We shall see that cooling of this region is the primordial limiting factor, mechanical fatigue being the next important one to consider.

Power dissipation in horn

The pulse repetition rate is

$N_c = 50$ Hz corresponding to $T_c = 1 / N_c = 20$ ms

If we assume that the damping is negligible (γ and δ being close to 0, the circuit is loss free), then the sinusoidal current discharge pulse is

$i = I_M \sin \omega_0 t \quad (0 < t < T_0/2)$ with $\omega_0 = 2\pi f_0 = 2\pi/T_0$

The pulse duration is $\tau_0 = T_0/2$

For simplicity, one assumes that the inner conductor is a cylinder of length l carrying a current sheet of mean radius R_m

The depth of the current sheet (skin depth) is

$e = k' /\sqrt{f_0}$

$e = k \sqrt{\tau_0}$

The resistance is

$r = \rho\ l\ (1 + \alpha\ (t-t_0))/ (2\pi R_m e)$

$r = K'\ l\ (1 + \alpha(t-t_0))/ (R_m \sqrt{\tau_0})$

The r.m.s. current in the horn is

$i_e = (I_M/\sqrt{2})^* (\tau_0/ T_c)^{1/2}$

The power dissipated in the horn is $P = r\, i_e^2$

$P = K\ l\ (1 + a\ (t-t_0))\ N_c I_M^2 t_0^{1/2} / R_m$ (P is proportional to $t_0^{½}$)

If a transformer is used,

$L_t = Lp + m^2 (L + Ls) \sim m^2 L$

Lp and Ls are the inductances of the primary and secondary side of the equivalent electrical circuit with an ideal transformer. Lp and Ls are considered to be negligible compared to L.

$\tau_0 \cong \pi (L_t\ C)^{1/2}$

$\tau_0 \cong \pi\, m\ (L\,C)^{1/2}$

$P = K\ l\ (1 + a\ (t-t_0))\ N_c\ I_M^2\ m^{1/2}\ (LC)^{1/4}\ / R_m$

If one wants to minimize the power dissipated in the waist, result shows that $m \geq 1$ should be taken to 1.

Direct discharge with no transformer provides minimum dissipation.

The relative importance of the effects of N_c , I_M ,R_m and τ are clearly visible.

4. Skin depth

Magnetic volume is confined betwen the inner and outer conductor.

With increasing frequency, the current flows almost exclusively on the surface of the conductor which is bounding the magnetic volume. The penetration depth is given by the formula :

$e = (\rho / (\pi f \mu_0 \mu_r))^{1/2}$

where: ρ = resistivity
f = frequency
μ_0 = permeability of void
μ_r = relative permeability of material

The total current is admitted to flow within this skin.

Following table applies to Al alloy ISO 6061 with $\rho = 0.048\ \Omega\ \mathrm{mm}^2\ \mathrm{m}^{-1}$

f_0 (Hz)	5000	4000	3000	2000	1000	500	100	50
τ_0 (μs)	100	125	166.6	250	500	1000	5000	10^4
e (mm)	1.19	1.33	1.53	1.88	2.66	3.76	8.41	11.9
P/P_{1000}	0.44	0.5	0.58	0.71	1	1.41	3.16	4.47

Mechanical thicknesses are, for all horns, considered bigger than the skin depth and conditioned by the mechanical design.

5. Charging voltage

Since heat load is a critical factor, design effort will be directed towards decreasing τ_0 as much as possible. This leads to an increase of charging voltage.

Horn voltage at t=0 :

The circuit being loss free ($R = 0$, $\gamma = 0$), the current simplifies to

$i = I_M \sin \omega_0 t$

The voltage across the capacitor bank is

$u = L di/dt$

$u = L I_M \omega_0 \cos \omega_0 t$

At t=0,

$\underline{U_0 = L I_M \pi / \tau_0 = K f_0}$

For a desired current I_M , charging voltage increases while pulse duration decreases.

The smallest t_0 value is conditioned by the highest charging voltage one wants to allow.

The intention is presently to limit the horn voltage to maximum 6 kV, keeping in mind that one wants to reduce it as much as possible.

6. Calculation of heat load

The closest realistic horn retained for calculation corresponds to type H40-400 (neck radius of inner conductor 40 mm and inner radius of outer conductor 400 mm)

The heat load is given in following summary table under P_H raw.
It is extracted from the more detailed electrical characteristics table in APPENDIX A and labeled "mean power dissipation in horn by current".

	Units	**H40-400**
Type	mm	**40-400**
Waist radius	mm	**40**
Peak current in horn	kA	**300**
Total capacitance for 1 switching section	µF	**1453**
Duty cycle	Hz	**50**
Pulse duration (half period)	µs	**93**
Charging voltage	V	**6283**
Voltage on horn	V	**4200**
r.m.s. current in horn	kA	**14.5**
P_H Mean power dissipation in horn by current *	kW	**39.**
Water flow needed In l/min with dq w= 15°C *	l/min	**37**

* power dissipation due to beam absorption to be added

7. Cooling

The inner conductor is cooled by spraying water on it continuously. Sprayers are distributed along external pipes and located in relation with the heat dissipation along the internal conductor. The water is collected by gravity into a tank situated below the horn.

The waterflow indicated corresponds to a temperature increase of **15°C** between input water at temperature Tin and collected water in the tank at temperature Tout.

The inner conductor is submitted to an incremental temperature increase during each electrical pulse. This increase is almost adiabatic and corresponds to the heat capacity of the conductor mass. In steady state, the energy deposited by each pulse is entirely transferred to the water flowing onto the conductor in the 20ms time window between two pulses.

7.1 Heat transfer with sprayed water

The final steady state temperature T_{ss} of the conductor depends on the thermal transmissibility factor h (in $w/m^2/K$) between the Al surface S of the conductor and the water film flowing along it, such that the heat transferred is :

$Q = h\ S\ \Delta\theta$ with $\Delta\theta = T_{ss} - T_w$

Tw is the water temperature along the conductor which we consider to be (Tout – Tin) /2 ~ 25 °C. Let us consider the cooling conditions of the horn waist which is generally cylindrical and calculate the resulting $\Delta\theta$ (Values are given for a cylindrical waist of length 0.1m).

Values of h can be found, in the literature, to vary between 1500 and 5000 w/m2/K. We retain h = 3000 w/m2/K which is indicated as the best value for tube heat exchangers or by calculation [5].

	Units	**H40-400**
Radius of waist	mm	**40**
Peak current in horn	kA	**300**
Duty cycle	Hz	**50**
Mean power dissipated in 0.1m long waist	kW	**6.**
Resulting $\Delta\theta$ for h=3000 W/m2/K	°C	**79.6**

The water is boiling since the temperature is at 79.6 + 25 °C = 104.6 °C.
Let us limit $\Delta\theta$ to 60 °C to avoid boiling. The heat which can be transferred is then :

	Units	**H40-400**
Heat transferred in 0.1m waist for $\Delta\theta$ = 60°C and h=3000 W/m2/K	kW	**4.5**

H40-400 is close to reaching the 6kW heat transfer needed. A smaller radius would clearly lead to excessive heating.
A factor of roughly 2 is missing if one wants to further reduce $\Delta\theta$. Solutions to improve the cooling of the horn then become unavoidable.

7.2 Water cooling fault

The adiabatic temperature increase for one pulse is
$Q = m\,c\,\delta\theta$
For Al, specific heat capacity is c = 0.896 kJ /kg/K
For 0.1 m waist length of mean diameter 0.074m and 0.006m thickness,
$m = 0.1 \mathrm{x}\ \pi\ \mathrm{x}\ 0.074\ \mathrm{x}\ 0.006\ \mathrm{x}\ 2700 = 0.38$ kg
For one pulse in horn H40-400, the Joule loss is Q = 120 J
$\delta\theta = 0.35$ **°C**
In the absence of water cooling and pulsing at 50 Hz, the time needed for the waist temperature to rise by 10°C is 0.57s, which would easily protect against such a fault.

8. Cooling improvement possibilities

One considers only classical cooling systems with de-ionised water excluding temperatures higher than 85 °C.

8.1 Installation of a second pressurised water channel

An additional closed water circuit can be studied and developed to provide a forced water cooling of the internal conductor waist. A thin Al alloy envelope (external to the magnetic volume) embeds into the inner conductor of the horn to constitute the second water channel according to the figure shown in APPENDIX B. The inner surface of the current carrying part of the waist may have a threaded profile to increase the heat exchange surface.

Heat transfer of channel 2
The heat which can be extracted through water channel 2 is:
$Q = h\ S\ \Delta\theta$
Take $\Delta\theta = T_{ss} - T_w = 60$ K
One assumes here that the water temperature along the conductor Tw is constant and ~ 25 °C.

The water temperature increase along 0.1m waist is
$\delta\theta = Q / m\ c$
For water, specific heat capacity is c = 4.18 kJ /kg/K
Q = 6 kW and m is the mass per second of water flowing along the waist
m = 0.33 kg/s (corresponding to a waterflow of 20 l/min)
Finally $\delta\theta = 4.3$ °C.
One can thus admit that the water temperature along the waist Tw is constant and ~ 25 °C, considering that the incoming water is around ~ 20 °C.
Take h ~ 2000 W/m2/K (typical value for water flowing through pipes with a 0.5 m/s velocity)
$S = k\ S_0 = k\ \pi\ \text{Diam}\ l$
With $l = 0.1$ m , Diam = 68 mm
Q ~ k 2.5 kW
The heat transfer along the 0.1m waist is now with both cooling channels
Qt = 4.5 + k 2.5 kW .
For k=1 , the transfer overcompensates the Joule losses and the waist temperature would stabilise around 76.5 °C.

8.2 Increasing the surface contact of channel 2

k = 1.5 is a surface increase factor obtained for example with threading.
Qt = 8.25 kW
The waist temperature would then further decrease to 68.6 °C.

The corresponding decrease of electrical resistance will then result in the temperature stabilising close to 65 °C which is acceptable. Deposition of energy due to the beam has however not been taken into account.

9. Cooling test

Values of h used in calculations need to be verified.

Measure heat transfer h with D.C. current on a 80 mm cylinder waist model for the mentioned cooling modes and later with the prototype subject to the heat load available in the test.

10. Electrical lines

A detailed study of the connecting lines between the powering stage and the horn (without or with transfomer) has not been done. **The line impedance which adds to the horn impedance is of prime importance.**

One has admitted for electrical calculations

line inductance	≤ 0.27 µH
line resistance	≤ 350 µΩ

11. Dynamical behaviour and mechanical fatigue

11.1Overview

H40-400 horn carries 300 kA of current in a pulse 93 µs long. The pulse repeats at 50 Hz (20ms between each pulse).
The horn is stressed by the superposition of differential thermal expansion and magnetic forces.

- The thermal expansion has a steady state component with the addition of an incremental temperature rise for each pulse. This incremental temperature rise is almost adiabatic (considering the 88 µs pulse) and is the result of Joule losses and energy deposited by the beam in the conductor.

- The magnetic forces reduce to a dynamic mechanical pressure problem. The magnetic surface pressure is a pressure pulse $p(t) = B^2/2\mu_0$ (in first approximation) with $B = \mu_0\ I(t)\ /2p\ r$. It induces vibrations in the structure. The pulse repeated at 50Hz pace should not propagate frequencies which match with the natural mechanical frequencies of the structure thus inducing mechanical resonances

Fatigue is finally the major design issue. The resulting maximum Von Mises stress in the structure should not exceed the limit of fatigue of the Al alloy used and corresponding to the minimum life time required of 2×10^{8} pulses.

The study of all the mechanical problems listed above is out of the scope of this note.

A simple approach to fix a first guess « waist thickness » is to calculate the total force and stress exerted in static mode on the waist. This value is not exceeded in dynamic mode if resonances are avoided, since dynamic containment is better than static containment. According to ref 6, dynamic containement $p(t) = B^2/2\mu_0$ is better than static containment by a factor T_M /T where T_M is the natural oscillating period of the structure and T =2x 93 µs the period of the discharge pulse. In our case it is very likely to be $T << T_M$.

Admitting that the beam entrance end plate is rigid and the other end plate flexible, the total tensile force exerted by magnetic pressure on the waist is $F = (\mu_0 I^2 /4\pi) \ln (Rout/Rin)$.
For H40-400 horn, Rout is 400mm maximum and Rin = 40mm. At 300 kA, F = 20700 N.
The outer diameter of the waist is 80 mm, the inner diameter being 68 mm for a waist thickness of 6 mm.
The section of the waist is thus π x 74 x 6 = 1395 mm^2 which leads to a tensile stress of 14.8 Mpa which is a good starting value (limit of fatigue for 10^7 tractions ~ 100 Mpa).

11.2 Mechanical tests and measurements

A prototype horn type H40-400 could be constructed and pulsed at 300 kA with one Hz fastest repetition rate re-using and completing existing equipment.

An existing pulse transformer will be used in a first phase to allow fast implementation of tests with the advantage of allowing measurements at low voltage. The resulting pulse length will not reproduce the real heating load but will provide a valid measurement of the heat transfer.

The stresses and the vibration modes can be measured at lower current and higher repetition rate with and without a transformer.

13. Conclusions

Staying in conventional horn technology without a pulse transformer and in view of a 50 Hz duty cycle, H40-400 with 40 mm waist radius and 300 kA, is the proposed design to perform experimental studies on the feasibility to operate high repetition rate horns.

Such a horn allows us to work with a steady state temperature around 65 ^{0}C in the hottest area of the inner conductor and its voltage remains lower than 5 kV.

An additional horn at 600 kA, producing an acceptable heat load with a waist radius of 200mm, may be added to improve the focusing performance [see APPENDIX C].

The heat calculations need to be assessed through appropriate tests to confirm the heat transmission factor values used.

A mechanical study has to be performed to evaluate the lifetime of the horn under fatigue. Dynamical mechanical stress and vibrational behaviour have to be calculated and confirmed by tests.

A study of power supply, switching arrangements [7] and pulsed lines have to confirm the validity of the operational mode envisaged, firstly for a test set up and secondly for a final installation.

14. Acknowledgements

Thanks are due to S. Gilardoni who defined the horn shapes. This note benefits from many helpful discussions in the Neutrino Factory Target and Horn working group chaired by B. Autin.

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APPENDIX A

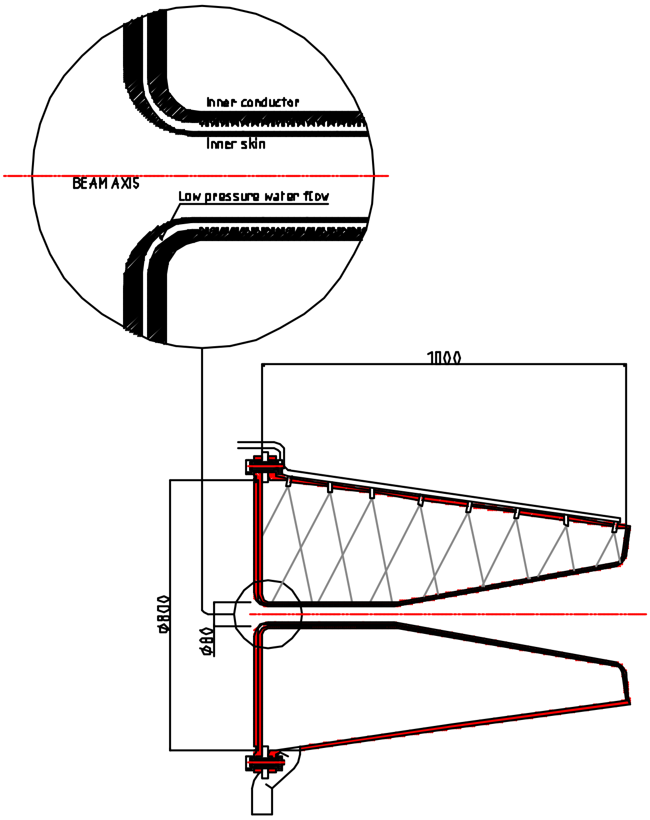
Detailed electrical parameter table of Horn H40-400 in comparison with Horn 25-500

	Units	Horn 25 - 500	**Horn H40-400**
Distance of capacitor & switching unit location	m	≤ 10	£ 10
Peak current in horn	kA	400	300
Duty cycle	Hz	50	50
Inductance horn	µH	0.46	0.41
Inductance additional	µH	0.27	0.21
TOTAL inductance	µH	0.73	0.62
Resistance horn at 100 ^{0}C	µΩ	228	183
Resistance additional	µΩ	349	287
TOTAL resistance	µΩ	577	470
Total capacitance for 1 switching section	µF	1090	1453
Pulse duration (half period)	µs	88	93
Skin depth	mm	1.1	1.25
Charging voltage	V	10500	6280
Energy stored in capacitor section	kJ	60.	29
Efficiency		0.61	0.64
Voltage on element	V	6550	4200
r.m.s. current in horn	kA	18.8	14.5

Mean power dissipation in horn by current *	kW	81	39
Water flow needed in l/min with dq w= 25°C *	l/min	78	37
Number of pulses in 1 month of operation		2 x 10^{8}	2 x 10^{8}
life time expected		10^{9}	10^{9}

* power dissipation due to beam absorption has to be added

APPENDIX B



NEUTRINO FACTORY HORN 1 - PROTOTYPE IV   Dimensions in mm

S Rangod 16/03/2001

APPENDIX C

Two stage horn

To remain compatible with standard horn construction and cooling techniques and not too far from usual operating parameter values, one has limited the current of the horn to 300 kA and increased the smallest waist radius to 40mm.

The focusing power of the horn being thus reduced with respect to [1], the idea is to compensate it with an additional outer stage horn at higher current and thus higher fields (600 kA for now) surrounding the horn under consideration which one calls now the inner stage horn.

Two alternatives seem possible :

10.1 2x300 kA outer stage horn (Oshorn1)

The higher 600 kA current of the outer stage horn can be obtained with a 2 x 300kA double skin horn (in fact a 2 turns horn) constructed as sketched hereafter.
The technical feasibility of such an assembly remains to be studied.
An immediate condition is that the voltage between the two skins should be low enough to enable insulation with ceramic spacers and interturn water cooling.
The pulse transformer is an interesting possibility to power the outer stage horn. It provides low voltage on the secondary side. The smallest radius of the outer stage horn is now big enough to avoid excessive heating in this area despite increased losses using a transformer.
Worth mentioning is that only the transformer has to be in the close area of the outer stage horn, whereas power supply, capacitors and switching unit can be located further away.

10.2 1x600 kA outer stage horn (OShorn2)

The usual single skin (or turn) horn is obviously simpler to construct, but one needs (unless using also a pulse transformer) to switch a 600kA current pulse compared to switching a 50 kA pulse in the previous case. The capacitor bank and switching unit have should be kept close to the horn to avoid long lines, otherwise the use of a pulse transformer becomes compelling.

Possible characteristics of an outer stage horn are shown in following table :

OUTER STAGE HORN	Units	2x300 kA outer horn	600 kA outer horn
Peak current in horn	kA	2x300 kA	1x600 kA
Duty cycle	Hz	50	50
Transformer		Ratio 6	No transf..
horn inductance	µH	1.76	0.44
Horn resistance at 75 ^{0}C	µΩ	41	44
TOTAL inductance with lines	µH	2.64	0.66
TOTAL resistance with lines	µΩ	102	111
Total capacitance for 1 switching section	µF	2724	16344
Pulse duration (half period)	µs	1600	320
Skin depth	mm	1.1	
Charging voltage	V	9500	3865
Voltage on element	V	1060	2576
Energy stored in 1 section	kJ	123	122
Efficiency		0.64	0.65

r.m.s. current in horn	A	59973	54191
r.m.s. current density in smallest section	A /mm2		
Total mean power dissipation in horn by current *	kW	164.	131.
Total water flow needed in l/min with dqw = 15°C *	l/min	157	125

* beam absorption losses to be added

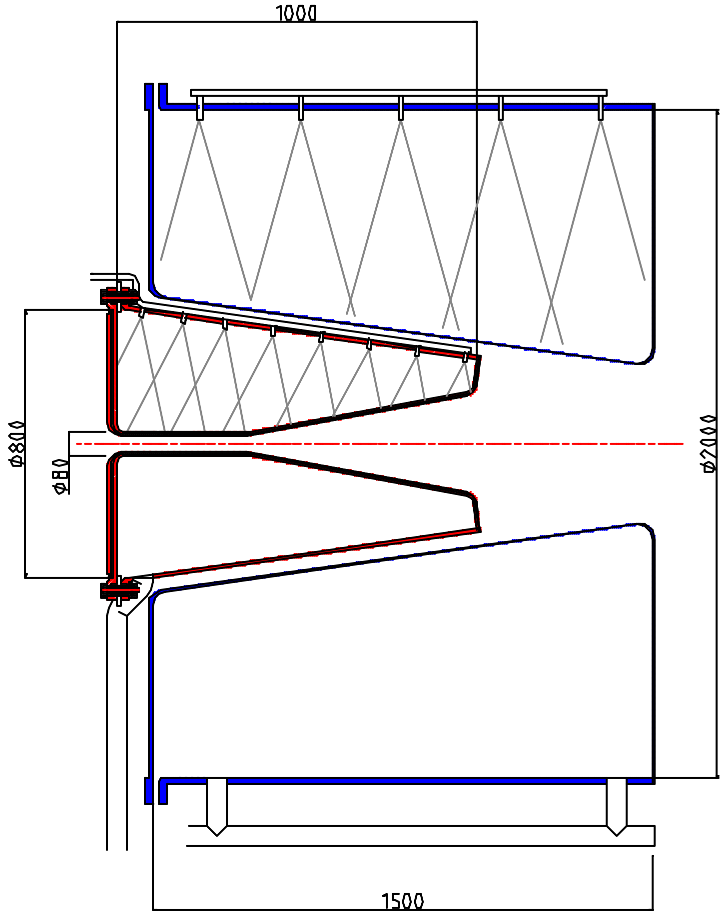
Voltage on the additional horn can also remain below 5 kV, but insulation between inner horn and outer horn becomes an additional constraint.

10.2 Heat dissipation and heat transfer in the 200mm waist region

One considers again a 100 mm long cylinder of 200 mm radius. Calculation of mean power dissipated in it and heat transferred with sprayed water cooling taking h = 2000 W/m2/K is recorded in next table :

	Units	**OShorn1**	**OS horn2**
Radius of waist	mm	200	200
Peak current in horn	kA	2x300	600
Current per skin	kA	300	600
Pulse duration (half period)	µs	1600	320
Duty cycle	Hz	**50**	**50**
Mean power dissipated in 0.1m long waist	kW	**3.8**	**5.9**
Resulting $\Delta\theta$ for h=2000 w/m2/K	°C	**15**	**23.5.**

Heating is thus not critical, but both solutions imply important constructional difficulties to be studied.



NEUTRINO FACTORY HORN – PROTOTYPE (V1A) Dimensions in mm

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