Development of high temperature induction ovens for ECR ion sources in Legnaro

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Abstract

A miniature induction oven is being developed in our laboratories, as an alternative to resistive oven conventionally used for metal feeding into ion sources. Since induction coil is physically separated from the sample to be melted, smaller contamination and longer lifetime are expected, even with corrosive sample and high temperature. Major limitation to efficiency is due to the dispersed flux. After extensive numerical simulation and theory the induction oven design have been optimized for efficiency; removal of intermediate heat screen (envisioned in the previous design concept) was found convenient in the overall.

1 INTRODUCTION

This article treats the optimisation and the solutions adopted during the construction of a miniature induction oven for ion sources, like the ECR (Electron Cyclotron Resonance) source in the I.N.F.N. Laboratories of Legnaro. Vapor pressure for optimal ECR working is about 10^{-3} mbar; for Praseodymium, chosen as element for first test, this implies a temperature of 1750 K well above its melting temperature of 1204 K. This behaviour is common to many elements including Iron and Uranium. Praseodymium was chosen because monoisotopic and reasonably high in atomic number (A=141). Final oven dimensions (size and position of coil and sample) come from a compromise between optimal heating of the sample, protection of induction coil and constructive experience with Tungstenum and Copper coils. Optimisation of size was determined both by analytical models and by numerical simulations, where we assumed a quasi-stationary approximation for magnetic RF field; that allows to use the computer code POISSON [1] as solver and TEKLNL [2] as post-processor. The resonant electrical feeding circuit was discussed elsewhere [3] and it is still unchanged. The working frequency is $f \simeq 400$ kHz in the case of Praseodymium (the corresponding penetration depth at 1750 K is 1 mm); this value can be changed for the other elements to be melted.

2 OVEN DESIGN

In Fig. 1 is shown the final drawing of the induction oven. A properly shaped Boron Nitride cup contains the sample to be melted; it is thus called the melted pot. The cup is shaped to have sufficient mechanical strength, but it is not too thick in order to minimise the gap between the sample and the heating coil and therefore to optimise heat production on the sample. A proper notch has been obtained in Boron Nitride to insert the end of a originally square section zirconia bar, whose other end is fixed into the water cooled surface of the cylindrical external copper box. The coil is obtained by carving a solid Copper tube. It consists of 15 turns and the conductor has a trapezoidal section (height 1 mm, 0.3 and 0.8 mm sides). Note that a 15 turn Tungstenum coil with a 0.5 mm diam wire was found quite unpractical. The coil is slipped on a Boron nitride cylinder which sustains and centres the coil, protects it against metal vapor and provides a thermal sink. A partially phasing internal capacitance is made by a Copper cylinder supported by three Alumina bars and is conveniently electrically connected. The external container, made in Copper, is composed by two parts, in contact with each other, to allow opening the oven for the sample replacement or periodical maintenance. Water cooling, flowing trough the lower plate, firmly keeps the external copper box below 350 K so that the box, besides being a RF shield, also protects the ECR source from radiated heating. Metal vapor jet coming out of the oven is limited by a Tantalum collimator. The shield of the coaxial line feeding RF power to the oven is connected to the lower plate of the oven; while inner cable terminates on the internal capacitance. Shield is made of Copper elbow and several

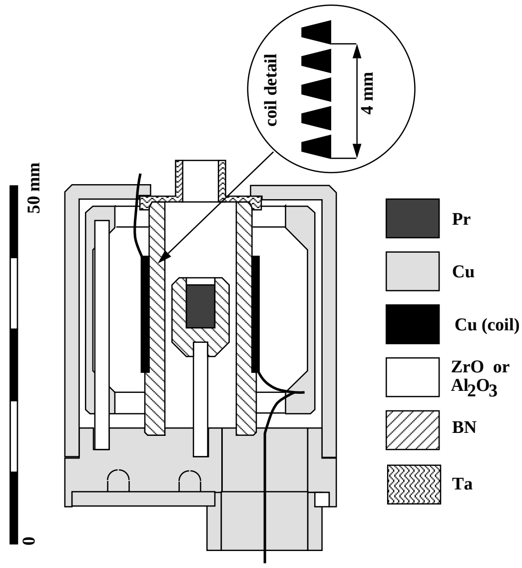

Figure 1: Section of the induction oven; with a detail of the coil

cylinders. A low cost RF feedthrough is welded on a CF100 flange which also contains the two water feedthroughs, two electrical auxiliary feedthroughs and two CF16 observation ports. The oven diameter is 19 mm and the height is 48 mm.

3 INDUCTION HEATING

As well known alternate fields (angular frequency ω) induce eddy currents in metallic surface [4]; when the penetration depth $\delta = \sqrt{2\varrho/\omega\mu_r\ \mu_0}$ is much smaller than conductor thickness, heat per unit area is

$$dP/dA = R_s(B_{\|}/\ \mu_0\ )^2 \quad (1)$$

with the surface resistance $R_s = \mu_r\mu_0\omega\delta/4$ and $B_{\|}$ is the magnetic induction parallel to the surface.

Since the wavelength is much larger than oven dimension, a quasi-static assumption holds $E \ll Bc$ and field can be computed as in a magnetostatic condition. The oven possesses cylindrical symmetry which make use of POISSON possible. On the conductor surface, (excluding the coil) a constant and zero vector potential was assumed $A_\vartheta = 0$; this because applied electric field is zero, and $E_\vartheta = -i\omega A_\vartheta/c$. A mesh size of 50μm was used in the sample region. Note that spatial resolution is most needed for computing superficial fields in the post-processor step of computation.

For the sake of generality, an uniform coil was assumed, with a total of current of one Ampere-turn; note that our actual coil construction satisfies reasonably this assumption, since we have 80 % copper on the inner side of the coil, where fields are higher. Also the coil thickness was chosen five times the penetration depth (0.2 mm at 800 K) in the coil, so that (1) holds approximately and we avoid the ohmic regime, where heat production is greater (at constant ampere turns).

From typical result of simulation we note that magnetic field assume the typical shape of a bean. Shaping of the internal side of the capacitance electrode, (besides from practical constraint) was also chosen to shape the return of the magnetic field line.

Let us call $H_i(T)$ the heating power which is dissipated in a set of conductor(s), assuming they stay at temperature T , as determined by surface integration of eq. (1). Here $i = 1$ be the sample, $i = 2$ be the coil, and $i = 3$ be the internal capacitance and the enclosure, more specifically the surfaces exposed to magnetic flux.

The size of the sample (radius a, length l) and of the coil (radius r_c length l_c) were varied in order to 1) maximize heat production on sample and minimise heat production on coil; 2) reduce the stored energy, that is to increase the power factor of the oven seen from the external circuit; 3) reduce the superficial area of the melting pot, for reason evident from thermal transport. It was obvious the need to decrease r_c and increase a as much as practical.

Following goal 1), the length of sample can be increased to offer a larger heating surface, until it exceeds the region of high field (the coil length minus some edge effect). Goal 3) and practical considerations suggested to respect $l < 6$ mm in our design.

As for the length of the coil, we compare some cases in Table I (note that we normalize result to one mJ of stored energy according to 2 and we gave results at some temperatures, including the extrema of the expected working range).

	sim.1	sim.2	sim.3	sim.4	sim.5
l_c	0.006	0.012	0.016	0.020	0.026
nI	362.3	444.4	493.9	541.8	615.3
$H_1(800)$	80.28	77.30	73.58	64.96	54.23
$H_1(1750)$	99.03	95.35	90.77	80.13	66.90
$H_1(2000)$	102.36	98.56	93.83	82.83	69.15
$H_2(300)$	10.67	11.11	11.31	11.43	11.80
$H_2(500)$	14.28	14.87	15.14	15.30	15.79
$H_2(800)$	18.64	19.41	19.75	19.96	20.65
$H_3(300)$	6.22	7.85	8.80	8.95	10.02

Table 1: Ampere-turns and heating powers $H_i(T)$ dissipated in electrodes at several temperatures , for five case, normalized for a fixed stored energy of 1 mJ; units are MKSA

A big reduction from previous result [3] in coil dissipation, due to the use of copper, is evident in table I , where, it is also evident that the rule $l_c = 2r_c$ gives a reasonably satisfying heat division, but $l_c = l$ gives slightly better results. Still the former rule requires a much lower current density in the coil, and it is preferable.

For the case $l_c = 16$ mm, we consider to use a $N = 15$ and half turn coil; from data of table we find the inductance $L = 1.97\mu$H of the oven, and the total resistance $R = 235$ mΩ, including coil skin effect resistance $R_2 = 39$ mΩ, resistance of the sample as magnetically coupled to coil $R_1 = 179$ mΩ and enclosure losses $R_3 = 17$ mΩ . We define the heat branching ratio $g_i = R_i/R$; so that $g_1 = 0.762$, $g_2 = 0.166$ and $g_3 = 0.072$.

3.1 Analytical model

An analytical model of the oven design was developed, even if only guidelines were published [3]. This model replaces the cylindrical sample with a prolate ellipsoid geometry; the only conductors considered are the coil and the sample.

For the sake of brevity and reference, let us remark that analytical model showed a slight preference of rule $l_c = 2r_c$; this optimization in favor of a relatively long coil is probably due to the model assumption of no obstacles on z axis for $z \to \infty$, while simulation accounts for enclosure effects.

4 THERMAL TRANSPORT

In order to obtain simplified estimate of thermal transport we assume that 1) only the melting pot has a temperature T_m high enough to radiate heat, while other bodies simply conduct heat; 2) emissivity e_m of melting pot is about 0.5; 3) a fraction $f_1 \cong 0.8$ of radiated heat is adsorbed by coil sustaining cylinder, which attains a maximum temperature T_c on its middle section; 4) since this section is in close contact with the coil, also the coil has temperature T_c; 5) the outer metal envelope stays at $T_r \cong 350$ K ; 6) melting pot and sample temperatures are equal, due to close contact.

Balance of heating power, radiative and conduction losses on melting pot gives immediately

$$g_1 P = A e_m \sigma T_m^4 + Y_z (T_m - T_r) \tag{2}$$

where A is the area of melting pot 4 cm^2, σ the Stefan constant, and $Y_z = s\sigma_z/\ell$ is the thermal conductance of the zirconia bar (section $s = 4$ mm^2 and free length $\ell = 9$ mm) equal to 5.7×10^{-4} W/K. We obtain $g_1 P = 106$ W for $T_m = 1750$ K, that is $P = 132$ W. Note the compelling reasons to minimize A .

Heating power balance on coil gives:

$$\begin{aligned} Y_c(T_c - T_r) &= f_2(g_2 P + f_1 A e_m \sigma T_m^4) \\ &\cong f_2(g_2 + g_1 f_1) P \end{aligned} \tag{3}$$

where Y_c is the heat conductance of the boron nitride cylinder, (section $S_n = 90$ mm^2 and length $L_n = 32$ mm), for a thermal load in its middle and cooling at its ends $Y_c = 2S\sigma_c/L = 0.163$ W/K ; the factor $f_2 \cong 0.75$ takes in account for effective distribution of heat production. We get $T_c - T_r = 480$ K which is still compatible with the use of copper ($T_c = 830$ K).

5 REFERENCES

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