INSTITUTE OF PLASMA PHYSICS
CZECHOSLOVAK ACADEMY OF SCIENCES

PROGRESS IN Z-PINCH RESEARCH

RESEARCH REPORT

IPPCZ-321

May 1992

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CZECHOSLOVAKIA

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RESEARCH REPORT

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CONTENTS

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INVESTIGATION OF INTENSE XUV EMISSION OF NITROGEN-PUFF Z-PINCH WITH SMALL ENERGY INPUT

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Abstract. Light elements like nitrogen or carbon are suggested as optimum working media for small Z-pinches (several kJ energy input). It is shown that such elements can be ionized up to K-shell ionization stages not only in hot-spots, but also in the bulk plasma. The yield of nitrogen K-shell radiation (about 10 J/shot) is therefore substantially higher than that of traditionaly used neon. Besides the pinch physics and radiation dynamics, such radiation could be of interest for applications in "water window" spectral region.

1. Introduction

In our previous experiments [1,2], a small linear Z-pinch device (present arrangement 5.4 μF, 4.3 kJ) with Ar or Ne plasmas starting from hollow gas-puffs was investigated as an intense pulsed source of XUV and soft x-rays [1]. The total x-ray yield from the pinched bulk plasma (≈ 1 mm in diameter, $n_i > 10^{19}cm^{-3}$, T_e ≈ tens of eV) was dominated by VUV radiation. Typically it was about 250 J/200 ns for Ar and 100 J/100 ns for Ne. On the other hand, K-shell radiation was observed only from hot-spots (tens of μm in diameter, T_e up to 1 keV, $n_e \approx 10^{21}cm^{-3}$), and a higher emitted energy was measured for Ne (spectral range 0.9 - 1.4 keV): 0.6 J/shot, while for Ar (spectral range 3.0 - 4.4 keV) only 0.05 J/shot.

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[1] The x-ray regions are marked differently by many authors. In this paper we will use VUV for photon energies 10 - 100 eV, XUV for 0.1 - 1 keV and soft x-rays for 1 - 10 keV region. Moreover, let us label all radiation of electron transitions to the K-shells, i.e. both K-shell lines and recombination continuum, as "K-shell radiation" or "K-shell region". Similarly the "L-shell radiation".

Because the K-shell output has an inverse dependence on emitted photon energy, a higher intensity of this kind of radiation as well as a lower background in VUV region can be predicted for elements lighter than Ne (i.e. working gases like propane, CO_2, nitrogen). The K-shell region of nitrogen, for instance, ranges approx. 400 - 700 eV, while the L-shell region practically coincides with the VUV range. In addition, there is a substantially higher chance to ionize these elements, due to their lower ionization potentials, up to He-like or even H-like state also in the bulk plasma by the same energy input. This can lead to a stronger effect of VUV background suppression in favour of K-shell radiation. Of course, we assume similar plasma parameters as mentioned above. For a rough orientation in radiative properties of the elements in question see Tab. I and Fig. 1.

Tab. I: Energies of first two electron transitions and ionization potentials of nitrogen ions. Note: for neon all the mentioned energies concerning He- and H-like ions are approximately two times higher.

Nitrogen	Be-like	Li-like	He-like	H-like
E_1[eV]	16	10	431	500
trans.	2s - 2p	2s - 2p	1s - 2p	1s - 2p
E_2[eV]	50	59	498	593
trans.	2s - 3p	2s - 3p	1s - 3p	1s - 3p
I [eV]	77.5	97.9	552	667

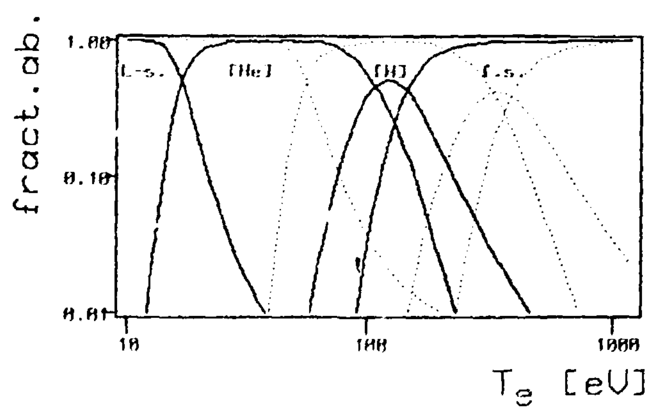

Fig. 1:

Calculated fractional abundances of L-shell (summed up), He-like, H-like, and fully stripped nitrogen ions in dependence on electron temperature. Dotted curves: the same for neon.

The purpose of this work was to obtain approximate information about the radiation of nitrogen Z-pinch as a basis for further investigation in this field.

2. Method, results and discussion

Four-channel system of vacuum X-ray diodes with metalic photocathodes (XRD) and spectral analysis by thin filters [3] were chosen as suitable tools for simple time-resolved radiation measurements in the whole spectral range of nitrogen-plasma intense emission, i.e. approx. 10-700 eV (see Tab. I). For individual spectral ranges different combinations of nitrocellulose (nt, 0.05-0.9 μm thick) and Al (1-3 layers of 0.75 μm foil) filters were used to achieve unambiguous spectral analysis. Spectral characteristics of the apparatus are shown in Fig 2. From the reduction of XRD signals by filters, some "effective" photon energies in individual spectral ranges were found out. This allowed us to derive time-dependent radiation intensities from the signal shapes and magnitudes. The reliability of results was improved comparing the experimental XRD signals with those calculated from the obtained intensities for all the filter-combinations used. The inaccuracy of absolute intensities determined by this procedure can be estimated to be a factor of 2-3.

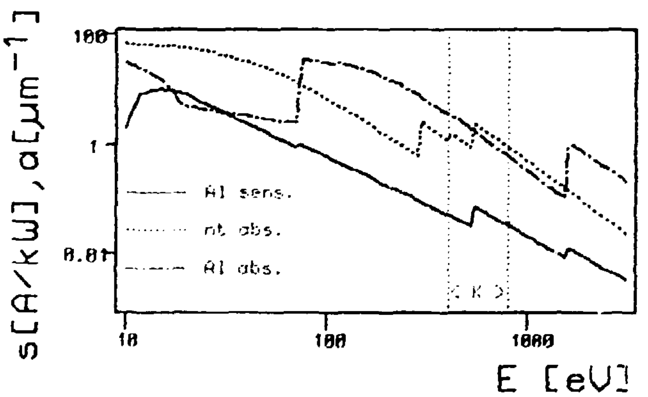

Fig. 2:
Spectral dependence of absorption coefficients of nitrocellulose (nt) and Al filters and of sensitivity of Al photocathode [4-6]. K-shell region of nitrogen plasma emission is marked.

The results reported here are taken from two Z-pinch regimes with current maximum 200 and 160 kA (risetime 1.2 μs), both starting from a hollow gas cylinder of length and diameter of 21 mm. Each regime was optimized by selecting suitable delay between gas valve opening and discharge switching on (here about 340-350 µs). In both regimes the pinch occurred near the current maximum.

In the "200 kA" regime the shots were quite good reproducible (the shapes and magnitudes of XRD signals within accuracy ±10 %). In Fig. 3 the comparison of XRD signals without and with various filters is shown. It is evident that by using thicker filters the portion of K-shell radiation in signals, with characteristic temporal structure (short peak) corresponding to hot-spots gradually increases in comparison with VUV background radiation.

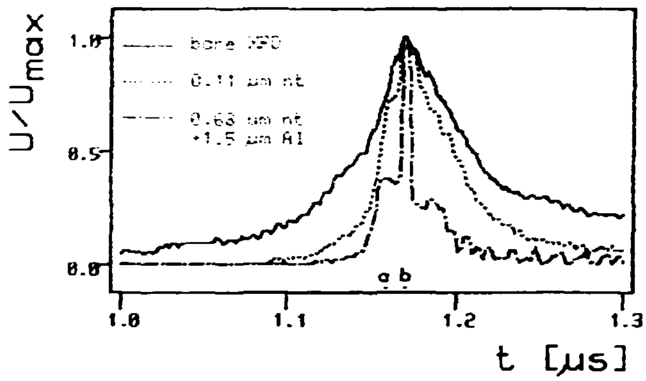

Fig. 3:

Typical XRD signals from nitrogen-puff Z-pinch: bare XRD (U_{max} = 50x4.4 V), channels with 0.11 µm nt (U_{max} = 22 V) and with 0.68 µm nt + 1.50 µm Al filters (U_{max} = 0.22 V).

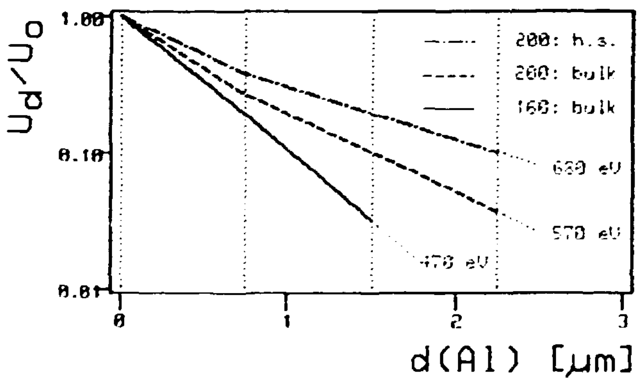

Fig. 4:

K-shell spectrum analysis by Al filters with 0.68 µm nt prefilter. Effective photon energies corresponding to the slopes are indicated.

In Fig. 4 the results of analysis of K-shell radiation by Al filters are demonstrated including 0.68 µm thick nt prefilter which is sufficient to suppress the L-shell radiation completely. The first maximum of K-shell radiation intensity (a in Fig. 3) is taken as a representative display of a bare bulk plasma not influenced by hot-spot radiation. At this instant the K-shell emission is evidently caused by a mixture of He-like and H-like nitrogen ions (cf. Fig. 4 with Tab. 1). The more rapid signal reduction by the first 0.75 μm Al layer can be interpreted as about 30 % of the intensity concentrated into the first resonant line of N [He] (430 eV); the rest between 500 and 600 eV is probably substantially influenced by recombination continuum in a narrow spectral interval above the ionization potential of N [He] (552 eV). The attenuation of mere hot-spot peak (i.e. after subtracting the main signal from the bulk, b in Fig. 3) seen from Fig. 4 shows a considerable amount of recombination continuum above the ionization potential of N [H] (667 eV), which indicates a non-negligible presence of fully stripped ions in hot-spot plasma.

The total energy output in K-shell region into 4π solid angle was about 12 J. Most of this amount was emitted from the bulk plasma in spectral range 400 - 600 eV during 50 ns pulse; the hot-spot radiation corresponds to about 1 J energy in spectral range 500 - 700 eV in a short (≈ 6 ns) peak.

Measurements with different sets of filters gave the "effective" photon energy of the dominant part of L-shell radiation between 50 and 70 eV. In this optimized regime only 20 % or less of the total intensity of L-shell radiation was indicated in the range of 2s - 2p resonant lines of L-shell ions. This is due to low abundance of these ions and/or collisional deexcitation which takes place at $n_e \geq 10^{18}$ cm^{-3} for such low-energy transitions [7]. From the comparison of radiation intensity attenuation by Al and nt filters follows that the emission between the L-absorption edge of Al (73 eV) and the first resonant transition of N [He] (430 eV) is not substantial. Total energy emitted in L-shell region was approx. 50 J in pulse duration (FWHM) about 100 ns.

The preliminary conclusions of spectral analysis enabled us to make following rough estimates of bulk-plasma parameters at maximum plasma compression, which could explain the observed time-dependent absolute radiation intensities. Ion density $n_i \geq 10^{19}$ cm^{-3} is composed of about 70 % of N [He], 20 % of N [H] and 10 % (probably in plasma periphery) of lower ionization stages (i.e. electron density $n_e \approx 5\ n_i$). At a typical pinched plasma cross-section 1 mm^2, the imploded plasma mass is about 10 μg. To reach an expected Bennett equilibrium the thermal energy needed is about 60 J which is comparable to kinetic energy of the imploded plasma shell at calculated final velocity about 10^5m/s (the total plasma internal energy is higher because some 20 J is "stored" in multiply ionized ions). Under the assumption of fully termalized plasma it corresponds to temperature of about 130 eV.

The results reported above evoked a simple idea that the line emission of N [He] has to be a dominant part of K-shell radiation at slightly lower electron temperature (cf. Fig. 1). This was the reason to operate the Z-pinch at somewhat lower discharge currents, typically 160 kA. In this regime the shot reproducibility was worse and the radiation analysis cannot be as detailed as in the 200 kA regime. Nevertheless, typical results of analysis of bulk plasma radiation (shown also in Fig. 4) confirmed our expectation. This means that in this regime the recombination continuum at higher energies is strongly suppressed; this could be important from the point of view of radiation sources.

To conclude, the presented measurements serve us as preliminary ones to realize more detailed investigation of Z-pinch with light working media and small energy input (see [8]).

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MULTICHANNEL X-RAY SPECTRAL MEASUREMENT OF HOT PLASMA EVOLUTION IN NITROGEN-PUFF Z-PINCH

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Abstract. Soft x-ray emission from nitrogen plasma of gas-puff Z-pinch device (with energy input 4.3 kJ and current 160 kA) has been studied. Multilayer mirror polychromator with time-resolved registration by PIN diodes was installed and its relatively narrow spectral windows were aligned to the important parts of nitrogen spectrum between 390 and 710 eV. The T_e evolution (≈400 eV in hot spots) was measured from a slope of recomb. continuum of He-like N. The T_e of bulk plasma (≈100 eV) is compared with T_e calculated from yields of K-shell lines. Moreover, pinhole cameras were used for better understanding the radiation phase of the pinch. Time sequences of peaks in x-ray signals corresponding to a number of bright spots on photographs, are presented.

1. Introduction

Z-pinch plasma is, undoubtedly, quite complicated subject of research. It is too small to be investigated by a dipped probe, too dense (esp. inside the hot spots) to make good laser interferometry, and it is very short-living object which limits the choice of the applied techniques of measurement and/or the results obtained. Fortunately, Z-pinch plasma is also very intense pulse source of radiation. Our previous experiments with Ar and Ne allowed us to estimate plasma parameters [1]. Though it gave quite consistent data about the pinch, only time-integrated x-ray diagnostics (spectra and pinhole photographs) are not sufficient to study the Z-pinch nature. Advanced diagnostics, i.e. spectrally or spatially resolved methods, joint with temporal resolution, have to be used. Therefore, after preliminary measurements with nitrogen [2], we installed such a diagnostic tool.

2. Experimental

A conventional small gas-puff Z-pinch device was operated in the regime with current 160 kA which promised to produce more He-like K-shell line radiation and less continuum radiation than in 200 kA regime [2]. About 1 cm^3 of nitrogen was injected in the form of a hollow shell (diameter and length 21 mm) between the electrodes and then imploded by the capacitor bank energy 4.3 kJ.

The absolute x-ray measurements were carried out by multichannel polychromator described in [3]. Each of 4 channels consisted from a submicron filter, multilayer mirror (MLM) and a PIN diode. The emitted spectral power density into 4π Sr is then

$$dP/dE = I_{PIN}\, 4\pi L^2/\bar{T}_F(E) . \int R(E)dE . \bar{S}_{PIN}(E) \qquad [W/eV],$$

where $\bar{T}_F(E)$ is average filter transmission in the channel with energy interval ΔE, $\int R(E)dE$ is integrated reflection coefficient of MLM, $\bar{S}_{PIN}(E)$ is average PIN diode sensitivity within ΔE, L is source-to-MLM-to-detector distance, and I_{PIN} is detector current. A maximum error in the dP/dE determination is connected with the accuracy of the values T, R, S, L, and with an alignment of the channel. Here the total error of the dP/dE did not exceed 27 %.

The thickness 0.3 - 0.6 µm of used light-tight filters was sufficient to absorb a scattered low-energy component of x-rays. Filter transmissions as well as the reflectances of the dispersi-

energy	392	430	500	540	573	650	704	930
filter	Ti	Sn	Sn	Fe	Cu	Cu	Cu	Al
T_F	0.16	0.21	0.25	0.09	0.05	0.10	0.18	0.20
$\int RdE$	0.67	0.41	1.85	1.80	3.03	2.16	4.70	1.29
$S_{CH}x10^{-3}$	0.65	0.6	4.02	1.53	1.53	2.38	9.84	3.4

Tab.I: Data of used polychromator channels - filter transmission T_F, reflection of MLM, and channel sensitivity S_{CH} [A.eV.cm^2/W].

ve elements (MLM) were calibrated by x-ray grazing incidence monochromator in the range 270-940 eV (tab.I). The W-Si MLMs (R_{max}= 0.03-0.15, 2d = 72-78 Å, $\Delta E/E$ = 0.03-0.05) can be advantageously used in broad energy range owing to smooth spectral dependencies of scattering factors of W and Si up to K-edge of Si (1.84 keV). Silicon PIN diodes (dead layer 0.15 µm) have the time resolution 1.2 ns. The absolute calibration of their sensitivities (0.003 - - 0.013 A.cm^2/W) was carried out by photoionization quantometer [4]. The polychromator was placed 195 cm radially from the pinch.

3. Results from polychromator measurements

Four-channel polychromator was used in the experiment with different combinations of channels from tab. I. An attention was paid especially to the channel couples covering the basic K-shell lines (tab. II) or recombination continuum above the ionization potentials of He-like or H-like ion species. Signals acquired by the couple of 573/650 channels (fig.1) enabled us to calculate T_e evolution from the slope of the x-ray continuum (fig.2). A stable component of T_e (about 100 eV) corresponds to the bulk plasma, which is a long-living formation in comparison with hot spot(s).

ion	trans.	E/λ[eV/Å]	trans.	E/λ[eV/Å]	I [eV]
He-like	1s - 2p	431/28.8	1s - 3p	498/24.9	552
H-like	1s - 2p	500/24.8	1s - 3p	593/20.9	667

Tab.II: Principal data of nitrogen K-shell spectrum: main transitions, line energies and ionization potentials (after [5]).

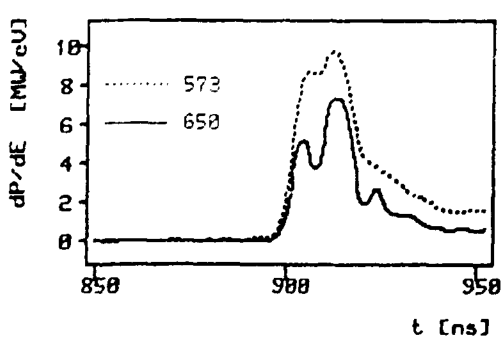

Fig.1: Power densities detected in channels aligned to energies 573 and 650 eV.

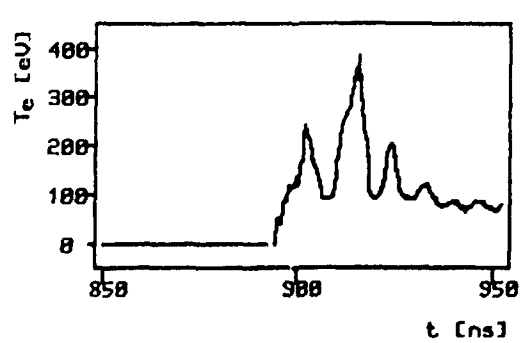

Fig.2: Time dependence of T_e calculated as a ratio of the power densities from fig.1.

To better understand ionization and radiation in Z-pinch, an attempt was made to compare experimental results with theoretical ones from computer code RATION [6]. Evidently such a steady state model of hot dense plasma radiation can give a reliable estimate of plasma parameters just under the assumption that the tempera-

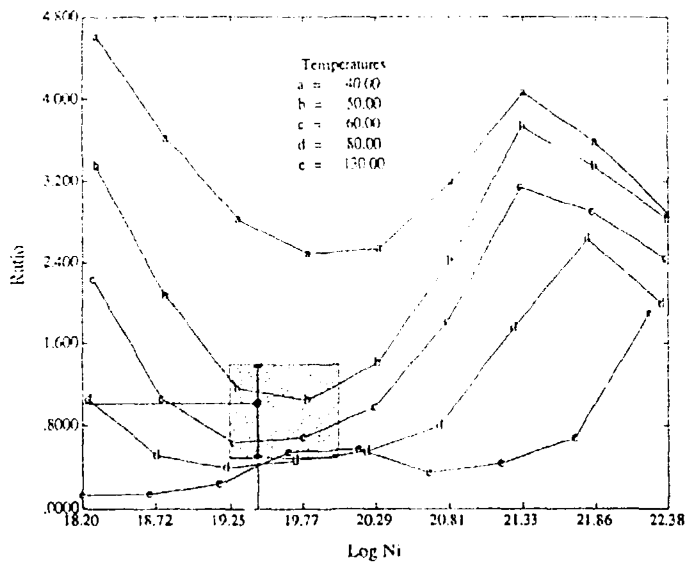

Fig.3: Ratio of total energies emitted in two pairs of important K-shell lines at 431 and 500 eV (see the text and tab. II) in dependence on N_i for different T_e. Experimental value of this ratio is taken from polychromator channels 430/500. A dotted area marks a range of ion densities N_i possible in our experiment.

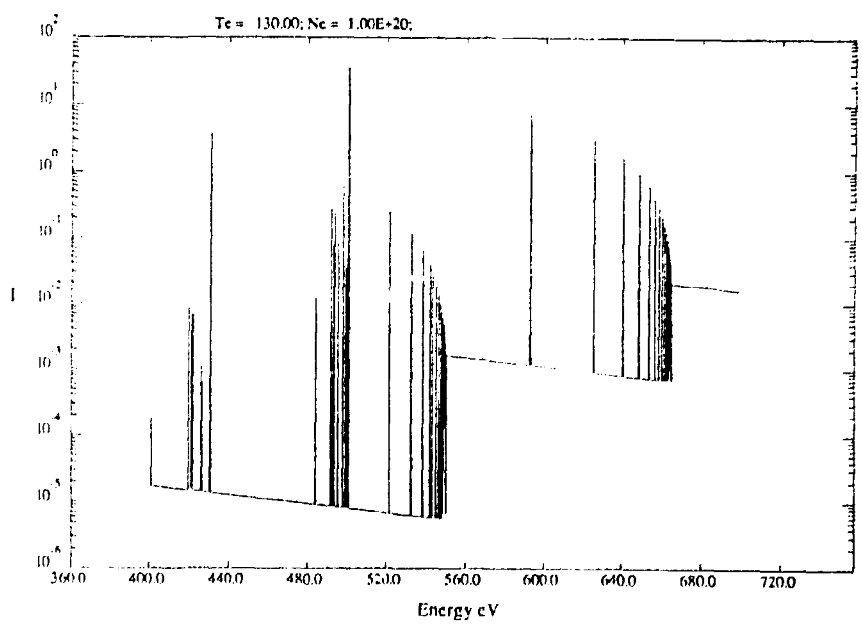

Fig.4: Nitrogen x-ray spectrum computed for steady state non-LTE conditions from [6] for plasma parameters taken from paper [2].

ture and density gradients are small during observed emission. Of course, the fulfillment of this condition in Z-pinch is rather limited. A ratio between the radiation yields in channels at 430 and 500 eV (covering He-like resonance and intercombination lines and both the lines close to 500 eV, respectively) was compared with the plot of different plasma parameters (fig.3). The experimental value of this ratio, tailored to a bulk ion density calculated from simple dynamics of Z-pinch plasma implosion indicates bulk plasma T_e somewhat lower ($\approx$ 50-60 eV) than mentioned above. This discrepancy may consist in unknown portion of continuum backing all the lines as well as in a deformed data in 650 eV channel due to a lot of merged lines of H-like 1s-np series. The simulated spectrum in fig.4 can give a rough image of the reality.

4. Pinhole photography

a) b)

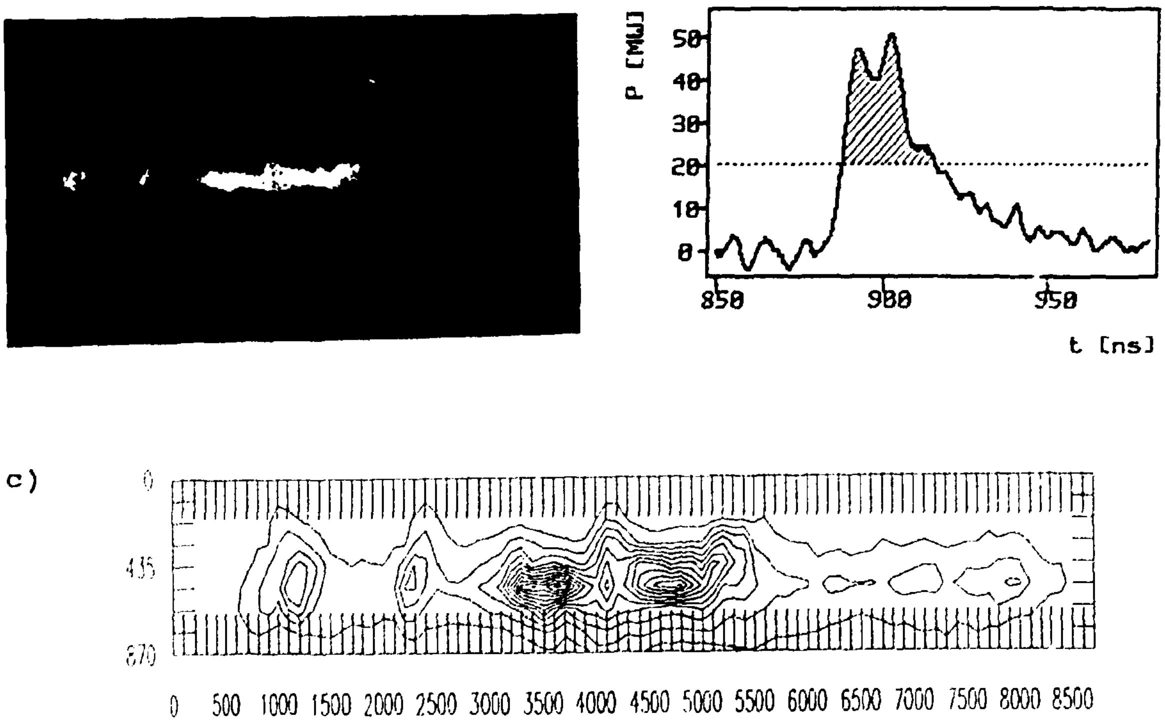

Fig.5: a) Enlarged pinhole photograph through 7.5 μm Be filter.
b) X-ray intensity evolution in polychromator channel 430 eV during the same shot. The part of radiation responsible for the strong darkening of film by hot spots is hatched.
c) Contour plot of spots area as in a). Scale numbers are in μm; actual dimensions of the plasma formations are 0.65x smaller.

For independent x-ray measurements, 2 pinhole cameras (with entrance diameters 51 and 58 μm, different light-tight filters and x-ray film Agfa Structurix D 8) were placed 15 cm from pinch axis. Besides the "clouds" of bulk plasma there are also sharply bounded bright spots on the photographs. Their occurrence coincides with the shots providing the radiative powers from the polychromator channels higher than approx. 20 MW. Also the number of the hot spots agrees well with a sequence of peaks in polychromator signals above this limit (fig.5 b).

5. Conclusion

The soft x-ray radiation carries rather detailed information about the plasma properties but a lot of ambiguities as well. In order to interprete the information properly, it is inevitable to analyse the radiation trying to decide what portion of it has an origin in the bulk or the hot spot plasma, in the continuum or the line emission. The value of bulk plasma T_e should be therefore precised by better alignment of polychromator channels to the parts of continuous spectrum without lines. The T_e found out during hot spots lifetime (fig.2) is lower than that in Ar [1] because the dimensions of bright plasma formations (fig. 5a) are much larger. To obtain full information about the appearance and evolution of hot spots, temporal resolution of the picture (e.g. x-ray streak camera, set of gated microchannel plates etc.) is desired to use simultaneously with the polychromator.

The authors would like to thank Drs. Pfeifer and Člupek for help with computation and one of them (OR) to Dr. Lee for providing an up-to-date version of code RATION.

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X-RAY EMISSION SCALING AND ENERGY BALANCE OF SMALL GAS-PUFF Z-PINCH

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Abstract. Gas-puff Z-pinch is discussed as an intensive pulsed source of soft x-rays. Measurements of total x-ray yield Y_T and the yield Y_K from K-shells of highly-ionized atoms of argon, neon, and nitrogen are presented. The radiation produced by small (4.3 kJ) gas-puff Z-pinch confirmed the $Y_K \approx I^4$ scaling (well-known from large devices) also for pinch currents I = 120 - 200 kA. The yield Y_T scales as I^2. Some basic considerations about energy balance of Z-pinch as well as similarities between terawatt and gigawatt devices are expressed.

1. Introduction

The x-ray emission scaling and the energy balance of Z-pinch have been recently discussed in several articles, e.g. in review article [1] or in more specialized papers laying stress on the x-ray yield versus discharge current and initial radius [2], and the x-ray yield versus atomic number [3]. These considerations have resulted from the measurements on large (terawatt) Z-pinch devices, especially on that with the exploding wires. Nevertheless, also neon- and argon-puff Z-pinches gave the $Y_K \approx I^4$ scaling including an interesting transfer to $Y_K \approx I^2$ scaling if applied high currents above circa 2 MA (see fig. 1). Hence, it is quite logical to put and try to answer this question:

IS THE I^4 SCALING OF K-SHELL RADIATION VALID ALSO FOR SMALL GAS-PUFF Z-PINCHES ?

It is necessary to distinguish between the x-ray radiation of pinched bulk plasma and that of hot spots plasma. Basic parameters of these plasmas are different as well as their time scales. In small gas-puff device the bulk plasma is too cold to ionize K-shells of neon or even argon ions. The image of bulk plasma, therefore, is not visible on pinhole photographs taken in keV-region [4]. On the contrary, the conditions in the hot spots are sufficient for K-shell ionization, however the mechanism of their stochastic creation (either m = 0 sausage MHD instability or radiative collapse) is not fully clear yet. In spite of small energy input in such Z-pinches, these devices enable us to study the plasma in almost the same unique conditions (i.e. high densities, enormous magnetic fields, He-like and H-like ionization states and their radiative properties) as in large terawatt devices, but here only inside very small volumes of the hot spots. Of course, the elements lighter than neon can be ionized up to K-shell states even in bulk plasma of small Z-pinch [5].

Thus, here was a possibility to extend the K-shell yield versus current scaling also for gigawatt Z-pinches and to examine the validity of simple relation $Y_K \approx I^4$.

2. X-rays scaling

As it was measured by our bare x-ray diode (XRD) with aluminium cathode (ϕ 20 mm), for pinch currents between 80 and 200 kA the total x-ray yields from bulk plasma Y_T scale as I^2. The coherence between Y_T and a magnetic field pressure on the border of bulk plasma (taken from bennett equation) or a work done by electromagnetic piston during the implosion of plasma layer (taken from snowplow model), which both are proportional to I^2, is then obvious. A crucial fraction of Y_T consists of recombination (free-bound) continuum as well as quasi-continuum of merged L-shell lines and 2s - 2p lines from several ion species in the spectral range of tens eV. An up-graded arrangement of our gas-puff Z-pinch (5.4 µF, 4.3 kJ, 40 kV, t/4 = 1.2 µs, initial hollow gas cylinder length to diameter: 20/32 mm) made higher x-ray output possible than that reported before [6] - see table 1. In the case of argon the reached energy 250

J/shot corresponds to an average x-ray power 1.3 GW during a pulse of some 200 ns FWHM. The conversion of total electric energy of capacitors into the x-rays thus achieves 6 %, or even 12 %, if we consider only the net magnetic field energy participating in the plasma implosion (i.e. without the energy losses in the circuit, in spark gaps etc.).

The K-shell emission, generally said, comprises all radiation of electron transitions to the K-shells, i.e. both K-shell lines and recombination continuum. Our K-shell radiation measurements were carried by calibrated semiconductor PIN diode (ϕ 9 mm) placed 176 cm radially from pinch z-axis. The detector has been fabricated with 0.2 μm light-tight Al layer. In addition, beryllium filters either 7.5 μm (for Ne) or 110 μm thick (for Ar) have been used to cut off the photon energies of L-shell transitions. Somewhat more complicated measurements of nitrogen K-shell emission by XRD are described in [5]. The radiation yields Y_K from the K-shell transitions of few-electron ionic species of N (photon energies 0.4 - 0.7 keV), Ne (0.9 - 1.35 keV), and Ar (3.05 - 4.4 keV) are included in tab. 1. The FWHM of these soft x-ray pulses amounted about 15 ns for Ar and Ne, and about 6-10 ns for N, respectively.

x-rays	Ar	Ne	N
total	250	100	60
from K-shell	0.05	0.6	12

Tab. 1. X-ray yields into 4π solid angle (in Joules/shot) from gas-puff Z-pinch at discharge current 200 kA.

All the x-ray yields mentioned above have been obtained at the pinch current 200 kA. Thus, it was desirable to go down to lower currents to prove the $Y_K \approx I$ scaling. The results are shown in fig. 1 for all three gases. Supposing the validity of the $Y_K \approx I^4$ scaling, the scaling lines of Ar and Ne in fig. 1 have been extrapolated from the results presented in ref. [1, 2], and from references therein, respectively. It is seen that our measurements (marked IPP) hold the Ar and Ne lines satisfactorily

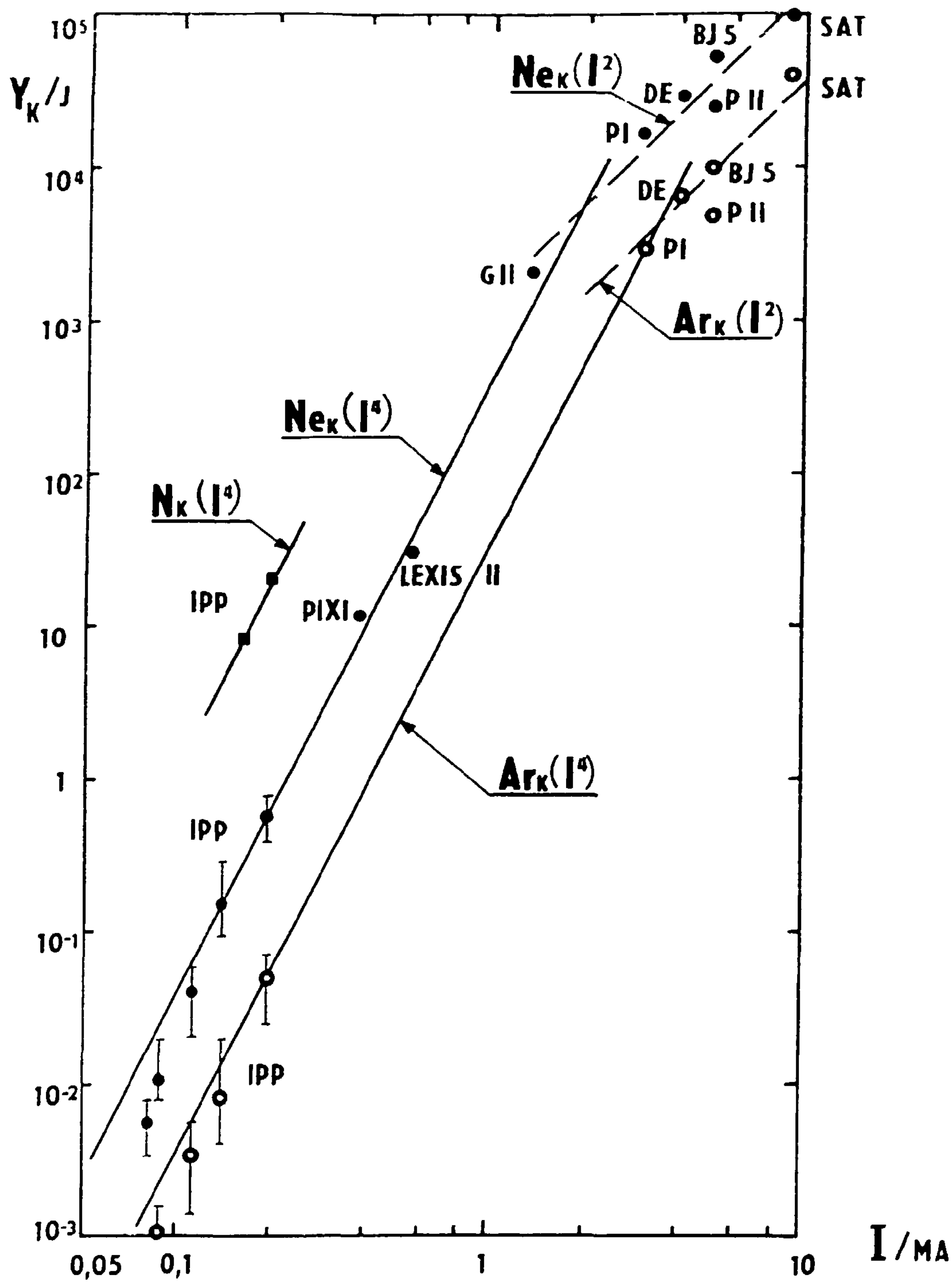

Fig. 1. X-ray yield from K-shell versus current in gas-puff Z-pinches with argon (hollow circles), neon (full circles), and nitrogen (squares), respectively. The hypothetical lines for $Y_K(I^2)$ scaling are also shown. Abbreviations of experimental facilities in the USA: SAT = Saturn (Sandia Nat. Lab.), BJ 5 = Blackjack 5 (Maxwell Lab. Inc.), DE = Double Eagle (Physics Int. Co.), P II = Proto II (Sandia), PI = Pithon (Physics Int.), G II = Gamble II (Naval Res. Lab.). PIXI and LEXIS II = commercial x-ray sources. IPP = Institute of Plasma Physics, Prague.

down to the currents $\approx$ 120 - 140 kA. Below a pinch current of approx. 120 kA the K-shell yields do not achieve the I^4 line, i.e. the dependence of Y_K is here stronger than before. Finally, at some 60 kA the Y_K is falling to unmeasurable values below the noise level of detector. Here we probably submerged into a range of critical currents below which the creation of hot spots (i.e. sources of K-shell radiation) is not possible if considered the model of radiative collapse only [7].

3. Discussion

A following objection could be said: the x-ray yield depends also on the mass loading, not only on the current! In majority, the pinches with gases work with line density of ions about 10^{20} m^{-1}, radius 1-2 cm, length 1-4 cm, valve plenum pressure cca 4 atm and also in a narrow interval of currents and current risetimes because of capacitor - load coupling [1, and the references therein]. Therefore, the data on x-ray yield could be considered as comparable and they are presented in this way [1, 2]. For the plot $Y_K \approx I$, there are used to take the value of Y_K for a given current in such a valve pressure when the Y_K was the highest [8]. So we did to make fig. 1.

All these considerations were done provided that <u>all the current is flowing through the profile of pinched plasma or the hot spots inside it</u>. The Y_K is then independent on its origin, either from bulk plasma or hot spots, on a creative mechanism of hot spots or the time sequence of their occurrence, if its time-scale is comparable with short hot spots' lifetime. Actually, it is an experimental problem to measure such high current densities over cross-section of a hot spot smaller than 50 micrometers!

4. On the energy balance of Z-pinch

In order to evaluate the energy balance during Z-pinch discharge, it is used to consider several components in the equation of conservation of energy. As usual, we have capacitive, resistive (ohmic) and inductive (magnetic) components of energy in the RLC circuit with time-dependent resistivity and induction

$L_p(t)$ of Z-pinch plasma. A portion of last component, $E_{acc} \approx I^2[dL_p/dt]$, accelerates the moving plasma like a piston (B-field work). It is obvious that this portion is equivalent to the kinetic energy of implosion. The energies of both ohmic heating and E_{acc} convert into the thermal energy of plasma, gradually during the implosion (especially in compressional pinches), or suddenly at the strike on axis (in the case of an ideal hollow plasma shell). The last and very complicated manifold process is thermal energy conversion to radiative energy (both continuum and line radiation in wide spectral range).

Let us estimate the energy budget for our small gas-puff Z-pinch with nitrogen. The snowplow model gives the imploded mass 10 µg and the final velocity of plasma shell $\approx 10^7$ cm/s, therefore the kinetic energy is $E_{kin} \approx 50$ J. The thermal energy of plasma with temperature 100 eV measured from K-shell spectrum [10] is comparable: $E_{th} = 3\ (\frac{1}{2}\ NkT) \approx 43$ J (for He-like bulk plasma ions, $N = N_i + N_e = 1.8 \times 10^{18}$). But the radiative energy, measured as Y_T, is higher: $E_{rad} \approx 60$ J (see tab. 1). Thus, the conclusion is the same as in terawatt Z-pinch [2]: the streaming kinetic energy cannot account all the radiation from plasma. In paper [2] the anomalous resistivity instead of Spitzer's one is suggested to remove this discrepancy. But we can take into account also other explanations.

First, the measurements of total radiation may be strongly influenced and hence overestimated by unisotropic character of radiation pattern, i.e. precise angular measurements are desired. On the other hand, a possible mechanism of kinetic energy loss is that plasma termalizes not only on the axis but partially also in the imploding shell of hollow gas-puff due to its finite thickness. Last but not least reason of the kinetic energy loss (or braking of the plasma motion) is energy conversion to the creation of few-electron ion species in plasma. As seen from tab. 2, this ionization energy "storage" is not negligible and has to be involved in any case as one of channels of energy transfer. It could play important role in free-bound radiation budget of Z-pinch. The importance of this has not been emphasized sufficiently till now.

ions	Ar	Ne	N
Li-like	112*	34*	8
He-like	153	46	13
H-like	351	103	39*

Tab. 2. Total energies (in Joules) "stored" in multiply ionized atoms of bulk plasma after inserting the energy of their ionization. Number of ions N_i in the bulk 3×10^{17}, all ions are assumed to exist in given ionization state. Upper limits for IPP Prague experiment are marked by *.

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