SYRINX - A RESEARCH PROGRAM FOR THE PULSED POWER RADIATION FACILITY

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ABSTRACT

Syrinx is a targeted research program with the objective to study, through practical examples, the fundamentals necessary to define the details of all parts which will be required for a new powerful plasma radiation source. The current level of activities of Syrinx is in the design and construction of a multi-megajoule class IES based pulsed power driver which will use long conduction Plasma Opening Switch technology. The present paper reviews mainly the basic experimental research of the POS and Z-pinch accomplished in the framework of Syrinx project. This work has a unique international level of participation, from conceptual designs to particular investigations.

INTRODUCTION

To provide for the radiation output expected to be of relevance in many applications, a pulsed power facility with a primary energy storage in the tens to hundred megajoule regime is anticipated. Apart from the simple consideration of costs, the problem of delivering electrical energy of this magnitude, from the storage region to the load region efficiently, is a formidable issue to be tackled. Among the issues of pulsed power science that one must address, one could group them under a number of headings; primary energy storage, energy transfer, secondary energy storage, closing and opening switches, power delivery, power concentration, energy to radiation conversion.

The Syrinx project was initiated in 1991 with join participation from CEG and LPMI. As a research program, it can combine an open-minded approach to new technologies and novel concepts, while guided by well established methodologies and expertises. A number of existing technologies are possible candidates for scaling up to the very high energy system foreseen. Primarily, the selection criteria is constrained by cost and efficiency. Inductive Energy Storage (IES) approach based on the Plasma Opening Switches (POS) technology seems to be rather attractive from the point of view of cost, while additional POS physical investigation should be done and aimed to optimize a POS at high power levels.

On the other hand, physical study and optimization of the Plasma Radiation Source (PRS) also represents a scientific challenge of the project. Existing Z-pinch facilities like Saturn is already producing radiation in the 70-90 TW region in the keV band with radiative energy in excess of 0.5 MJ [1]. New facilities coming on line could bring this figure to the 1 to 2 MJ regime. While a Plankian radiation spectrum may be desirable for some applications, it is sometimes not the most efficient way of utilizing the available energy resources in certain test environment, where the effect in a particular spectral band is to be studied. This has led in the past to extensive development of K-shell plasma radiation sources for emission in the 1-5 keV region. Above 100 keV, traditional beam-target bremsstrahlung sources have been successful in fulfilling the requirement. In between, the issue and the solution is not so clear. Particularly in the 10 - 40 keV region, where the efficiency of routine plasma radiation sources is low, efforts have still to be made to find an optimal solution. The Composite Pinch (CP) scheme being currently studied for Syrinx represents here one of the candidates for such PRS load.

LONG-CONDUCTION-TIME POS INVESTIGATION

The POS problem has been under investigation in the *Laboratoire de Physique des Milieux Ionisés, Ecole Polytechnique* (PMI) during the last five years [2]. We studied POS operation in coaxial and strip-line geometries on MAG-1 generator for the 0.5-1 μs conduction times and 200-400 kA conduction current level. Investigation of a 2 MA conduction current, 1μs conduction time POS was carried out in collaboration with *High Current Electronics Institute* on GIT-8 IES facility.

A 200-400 kA conduction current POS in cylindrical geometry

In this series of experiments the POS operated with electrodes in cylindrical geometry on the MAG-1 inductive storage generator [3]. A low-inductance capacitor bank provided at full charging voltage a 500 kA upstream current with a quarter-period of 900 ns into the switch. POS opening switched a 400 kA current with a 100 ns rise-time into a 25 nH inductive load.

In the series when plasma density diagnostic was applied the installation was charged at a lower voltage with the aim to decrease the level of electromagnetic noise. We used the laser interferometry as a diagnostics [4], and the time history of the line density integrated in the cordial direction was investigated. This approach allowed us to determine the geometry of the density evolution, to measure some temporal characteristics of this process and to compare them with the characteristic velocities of magnetic field penetration [5]. A typical time history of the line integrated density during the POS operation is shown in Fig. 1. This picture was obtained when the probe beam was located at the load side of the plasma, in the middle of the interelectrode gap. At this radial position along different axial locations of the probe beam the density time behavior was similar: after a certain increase it decreased till the absolute limit which could be resolved by our technique.

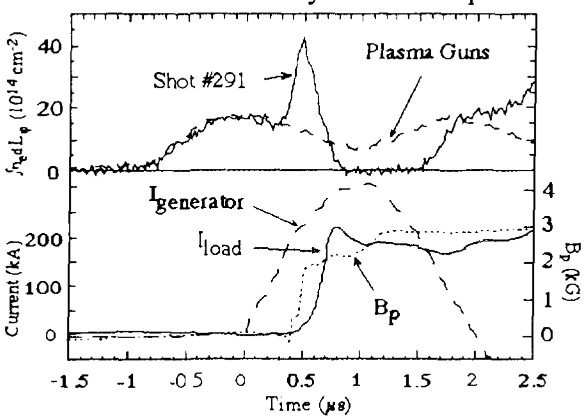

Fig. 1

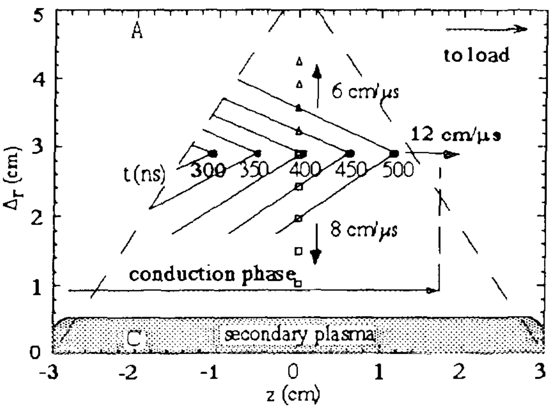

Fig. 2

Fig. 1. Measured time integrated density for the position of 2.9 cm from the cathode and 1.4 cm from the gun axis towards the load for the gun shot only (dashed line) and with MAG1 (solid line). There are also shown: upstream (I_g) and downstream (I_{load}) currents, magnetic field near the downstream plasma border (B_p).

Fig. 2. Reconstruction of the density maximum propagation through the plasma. Dashed lines indicate the initial plasma boundary. Moments of the peak maximum arrival are referred to the start of the upstream current.

The time sequence of the density maximum appearance with respect to the opening is shown in Fig. 2. The shock process had a wedge-like profile. The thickness of the shock front was estimated from the experiment with use of typical rise-time of the density peak ~100 ns and typical velocity in axial direction $u_f \sim 10^7$ cm/s, that gave $\delta \sim 1$ cm.

In case of magnetic field penetration into the bulk of plasma the ions can be considered to be motionless when the velocity of this penetration is higher than the Alfvén velocity, $u_f >> v_A$. Such theoretical solution does exist in frames of Electron Magnetohydrodynamics (EMH) [6, 7] where the magnetic field and electron current flow is governed by the Hall effect on the background of fixed ions. At the same time, such a "pure" EMH penetration (KMC-type [8]) cannot be accompanied by density perturbations. Another limit case (MHD shock-wave) corresponds to the density jump running away from the magnetic field piston. Most probably, our situation corresponded to the frontier case, when EMH criterion is satisfied at the magnetic field front, $\delta < \delta_i = c/\omega_{pi}$, and ions acquire velocities behind this front ($u_p(R) = v_A^2/2u_f$) (so-called Hall shock-wave [5, 9, 10]). We note, that the maximum piston velocity is reached when $u_p = u_f$ and corresponds to the snow-plow approximation with $u_p^{max} = v_A/\sqrt{2}$. With this consideration, a satisfactory explanation of the experimentally observed shock profile is obtained.

A 200 kA conduction current POS in planar geometry

On a new high-power inductive storage POS facility the plasma switch should be coupled to a magnetically-insulated transmission line (MITL) and a load. Planar geometry of the POS/MITL assembly would allow, in principle, more compact and less inductive design of a multimodule system. Plane geometry of the plasma switch was tested at 200 kA level of the conduction current on the two-module version of MAG-1 installation [11], Fig. 3.

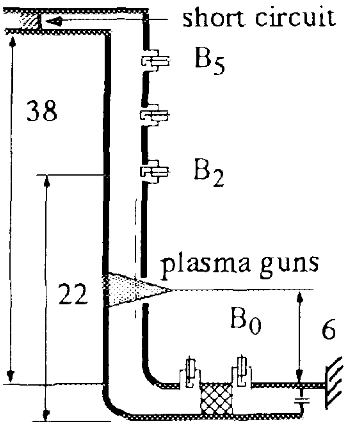

Fig. 3

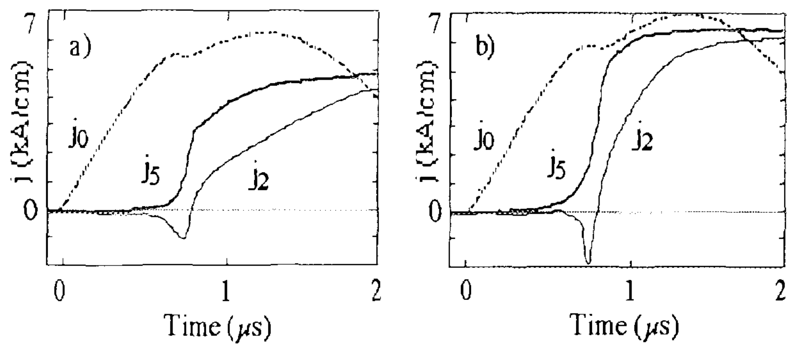

Fig. 4

Fig. 3. General design of one MAG-1 strip-line module (side view).

Fig. 4. Upstream and downstream current densities measured in the center of the anode for two cases: (a) initial configuration without the anode "wings", 16 guns, and (b) with the "wings", 10 guns.

In the initial strip-line configuration, the generator charging voltage of 30 kV yielded the maximum conduction current I_{0max} = 200 kA in one module, conduction time t_c = 700-800 ns and the opening time not less than t_s = 150-200 ns (Fig. 4a). Plasma current losses after the opening were as high as 10-20% of I_{0max}. In this configuration, in spite of initially homogeneous plasma injection, the plasma motion had different velocities in the center and at the borders of the strip-line. Therefore, relatively long opening time could be a result of asymmetry of our plasma system. To suppress this effect, we installed two additional anode "wings" in the plasma injection region. These electrode "wings" partially closed the opened strip-line borders and prevented the plasma to exit from the interelectrode gap. The opening became faster (Fig. 4b) and the plasma current losses became smaller. From our point of view, this fact confirms the influence of the initial plasma density homogeneity on the "quality" of the opening at least in the planar configuration of electrodes.

Synchronization of two modules with the help of a low-inductive upstream connection between them [12] was also verified experimentally. First, the synchronization was tested for the conduction time difference changing from 200 to 500 ns. In this case the rise-time for the sum of both load currents was shorter than in absence of the connection between the modules. Second series was performed when the initial plasma density and t_c were approximately the same for both modules. The result of this series was opposite to that of the first series. If $\Delta t_c < t_s$, the external upstream connection often made Δt_c even bigger. Therefore, one can conclude that the procedure of synchronization proposed in [12] was efficient only in the case when the difference of the conduction times of two plasma switches was bigger than the opening time of one POS.

A 2 MA conduction current POS on GIT-8 generator

High-current Plasma Opening Switch was experimentally studied on GIT-8 inductive generator in collaboration with *High-Current Electronics Institute* . The GIT-8 POS was operating at 2 MA current with the conduction and opening times of 1 μs and 100-150 ns accordingly. Interesting peculiarity of the GIT-8 POS was an axial plasma injection, towards the generator [13].

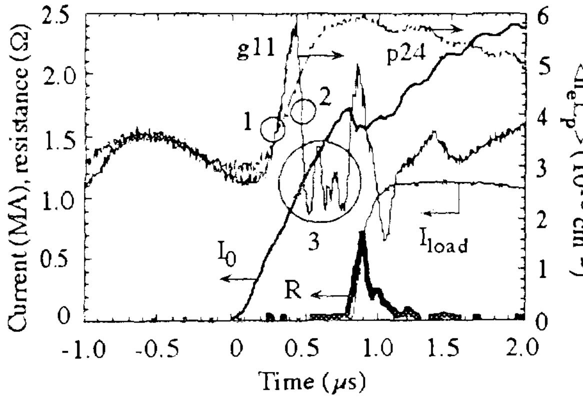

Fig. 5

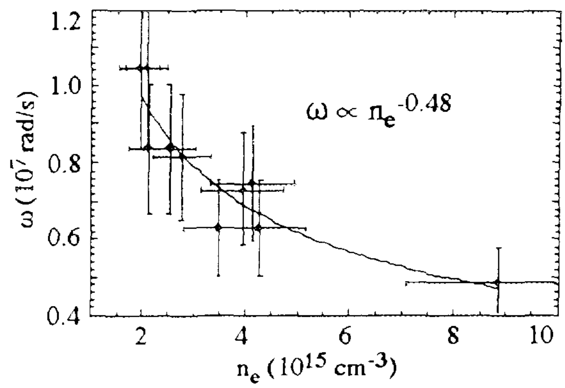

Fig. 6

Fig. 5. Typical plasma density behavior at Δ = 21.5 mm with the GIT-8 current (g11) and during the plasma guns firing only (p24). R denotes the POS resistance estimated as $V/(I_0-I_{load})$;

Fig. 6. Variation of the measured plasma density oscillation frequency with the averaged plasma density, $n_e = \langle n_e L_p \rangle / L_p$.

Plasma density was measured again with the help of interferometer described in [4]. The scene beam crossed from shot to shot the GIT-8 POS plasma along different chords at 28 mm from the plasma injection plane and at different radial positions of the gap, $\Delta = r - r_c$.

Typical time history of the line integrated density during the POS operation is shown in Fig. 5. Until the current starts to flow through the plasma channel and during 300-500 ns after the beginning of the upstream current, the line-integrated plasma density, $\langle n_e L_p \rangle$, follows the one measured during the gun firing only. Then, the density increases over the guns-only density (region 1 in Fig. 5) and drops abruptly (region 2). This fact can be an indication of the passage of a shock-wave through the point of measurements [5, 10]. Then, the linear plasma density rests almost at the same level as when the upstream current starts. The most interesting peculiarity of the plasma density behavior was an appearance of fast density oscillations with the characteristic frequency $\omega \sim 5\times10^7$-10^8 rad/s, prior and during the opening (region 3). Separate series with pulsed-power allowed identification and consecutive suppression of different sources of noise. The refraction effect could interfere only during and after the opening. Therefore, the earlier fast oscillations were produced by a real plasma process.

We applied also hard X-ray diodes to register Bremsstrahlung radiation produced by fast electron leakages along the plasma injection region. This electron leakage is the most intensive at the downstream plasma edge and allows its location to be determined [14]. The timing of X-ray radiation showed that the final POS opening process occurred in the region of plasma density measurements and the registered fast oscillation reflected some feature characterizing the opening process.

Fig. 6 demonstrates that the registered plasma oscillations strongly depend on the mean density. The function which fits the experimental data with the minimum absolute dispersion is approximately $\omega \sim n_e^{-0.5}$. Most probably, the measured oscillations were a result of hydrodynamic plasma instability having characteristic frequency equal to v_A/λ, where v_A is the Alfvén velocity, and the instability wavelength $\lambda \sim 0.5$ cm yields already an absolute value of frequency close to the experimentally measured. One of important consequences of this conclusion is that the well-known Hall plasma resistance may increase N times with respect to the value 30u/c [15], where $N = \Delta_{ak}/\lambda$ is the number of the plasma necks in the interelectrode gap Δ_{ak}.

POS optimization

For effective inductive energy storage the POS conduction time, t_c, should be close to the time of discharge of a given primary energy source. On the other hand, successful POS/load coupling on a new inductive storage facility is possible only with a preliminary information about maximum POS resistance and its rise-time, t_s. A number of empirical scalings for t_c value already exists and gives a satisfactory correspondence with the μs POS experiments (see, e.g., Refs. in [10]). However, existing relations for the conduction time often contain a free parameter which is chosen only after comparison with already realized plasma switch design. In addition, no theoretical estimate for the opening time of a μs POS exists for the moment.

Our point of view is based on the POS physics understanding represented in Refs. [5, 9, 10, 16]. In the long-conduction-time POS ($L_p > \delta_i$, L_p is the plasma length) the conduction phase is limited by the value $t_c = L_p/u_i \approx \sqrt{2}L_p/\langle v_A\rangle$, where $\langle v_A\rangle$ is the mean Alfvén velocity averaged over the conduction time. This value is determined by the maximum piston velocity which is realized in the interelectrode gap by the Hall shock-wave. In terms of the charge density passing through the cathode surface during the conduction phase, q/S_0 ($S_0 = 2\pi r L_p$ denotes the surface occupied by the injected plasma), the conduction phase is terminated when

$$\frac{q}{S_0} \approx 1.8\times10^{-11}\sqrt{n_p}\,\left(\frac{C}{cm^2}\right), \quad q = \int_0^{t_c} I\,dt \qquad (1)$$

where n_p denotes the ion density in cm^{-3} and the most widely used carbon plasma is supposed.

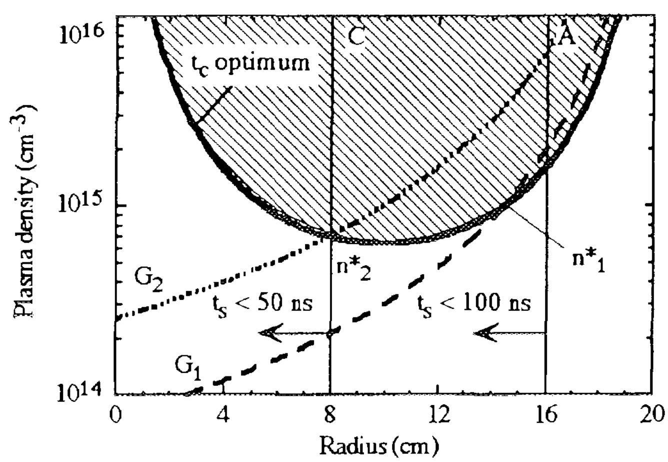

Fig. 7. Optimization of the POS configuration on the new inductive storage generator for h_g = 20 cm (see text).

At the end of the conduction time, when the plasma length which remains ahead the shock leading edge is small, $\Delta z < \delta_i$, the magnetic field starts to penetrate rapidly in front of the plasma piston and arrives to the load. The characteristic time of this process can be estimated for C^{2+} as follows [10]:

$$t_s = \frac{c}{\omega_{pi} u_f} \approx 3.2\times10^{-11}\frac{\sqrt{n_p}}{B}\,\delta_r \text{ (s)} \qquad (2)$$

where u_f is the KMC velocity [8], B is the maximum magnetic field in Gauss and δ_r expresses a strong interelectrode plasma density inhomogeneity ($\partial n_p/\partial r \sim n_p/\delta_r$), or the measure of curvature of the magnetic field lines in cylindrical geometry ($\delta_r \sim r/2$). If one substitutes roughly

$\delta_r \sim \delta_i$, a universal estimate can be obtained: $t_s \sim 1.25\times10^{-3}/B$. This signifies that for sufficiently fast opening ($t_s < 100$ ns) the magnetic field must exceed a certain value, $B > 10$ kG. To be more rigorous, this equation is an estimate of the plasma resistance rise-time, which can differ from the experimentally measured load current rise-time in case if the latter is "load-limited", $t_{Lexp} \sim L_2/R \geq t_s$ (L_2 is the load inductance and R is the resistance of the load circuit).

Comparison of Eqns. (1) and (2) with recent POS experiments requires additional information about the initial plasma density. Such comparison is presented in [10] and confirms Eqns. (1, 2) to be valid for rather large range of plasma switch characteristics.

An example of the diagram used to design the POS configuration in the project of a new six-module inductive storage generator is shown in Fig. 7 ($t_c = 0.7$ μs, $I_0 = 0.8$ MA for one module). Initial density profile in the gap ($n_g(r)$, or G_1 and G_2) is assumed to be known [4]. Therefore, $n_g(r)$ curves can be easily represented together with $n^*(r)$ curves defined by Eqn. (1) (n^* is the density corresponding to the optimum conduction time). Anode and cathode radii are chosen to have the opening time in the range 50-100 ns. The distributions G_1 and G_2 must satisfy inequality $n \geq n^*$ inside the interelectrode gap.

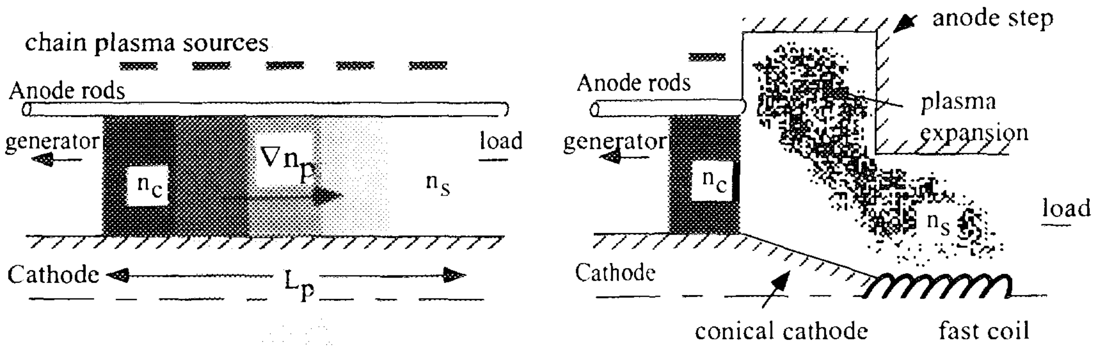

Fig. 8

Fig. 8. (a) Examples of the POS with extended length and axial plasma density gradient. (b) example of the plasma switch in PF and PFS configurations.

Fundamentally, the scalings (1), (2) allow better pre-definition of the POS geometry on an IES system in a project. Besides, these relations suggest several modifications of a POS in order to improve its performance (i.e. shorter t_s and higher POS resistance). First, a plasma switch with extended axial length, L_p, should be investigated. Then, a spatial decoupling of the plasma densities, n_c and n_s, "responsible" for the duration of the conduction and opening phases should be incorporated accordingly. Such decoupling might be done through an axial plasma density gradient, directed from a generator to a load (Fig. 8a), or by using the axial plasma motion and plasma expansion during the conduction phase (Fig. 8b). In the last case, the POS geometry resembles somewhat the Plasma Focus (PF), or Plasma Flow Switch (PFS) configurations.

INVESTIGATION OF THE COMPOSITE Z-PINCH

The simplest CP consists of two parts [16], an external hollow cylindrical plasma of fairly low density and an axial high-density plasma core. During the shell compression, RT or m = 0 MHD instability is supposed to form rarefied regions in the local plasma density. When the plasma thickness in front of the instability leading edge becomes smaller than c/ω_{pi} one should describe this plasma in the frames of Electron MHD [7]. Electrical resistance of these plasma "necks" can be estimated as the so-called Hall resistance [15]. This resistance provides a current, I_z, on the axial core with the following characteristic rate of rise

$$\frac{dI_z}{dt} = \frac{c/\omega_{pi}}{\lambda}\frac{I_0}{t_c}\frac{1}{2\ln(r/r_c)} \qquad (3)$$

where λ is the macro-instability wavelength, I_0 is the generator current, r is the shell radius at which the disruption occurs, r_c is the CP axial core radius and $t_c = r/v_s \sim r/v_A$ is the additional compression time of the external shell after its disruption (v_A is the Alfvén velocity). In addition to the Hall potential there is also a reactive resistance $|dL/dt|$ (L is the inductance between the inner core and external shell) which can increase I_z. This term can be important in case of vanishing of the described disruption.

Therefore, if the disruption occurs at small residual distance between the external shell and the inner CP core and at sufficiently high value of the generator current I_0, dI_z/dt can reach much higher values than dI_0/dt, as given by Eqn. (3) This CP property promises already higher homogeneity of the axial core if compared with EW regimes and harder X-ray radiation than in the liners. Indeed, the experimental results demonstrated higher hard X-ray power to be produced by a high-temperature/density uniform plasma [17].

Composite Pinch experiments on GIT-4 generator

Experiments were carried out on GIT-4 inductive storage generator [17]. The technical purpose of this series of experiments was to obtain a powerful homogeneous PRS radiation in the near- 10 keV region. The Plasma Opening Switch (POS) provided a 1.5 MA current with the rise-time of 150 ns into a CP load. External plasma was formed by a hollow preionized double-shell Ar liner with varying linear masses of both shells. Inner axial core consisted of metal Al, Ti, Ni and W wires with linear masses in the range of 30-90 μg/cm.

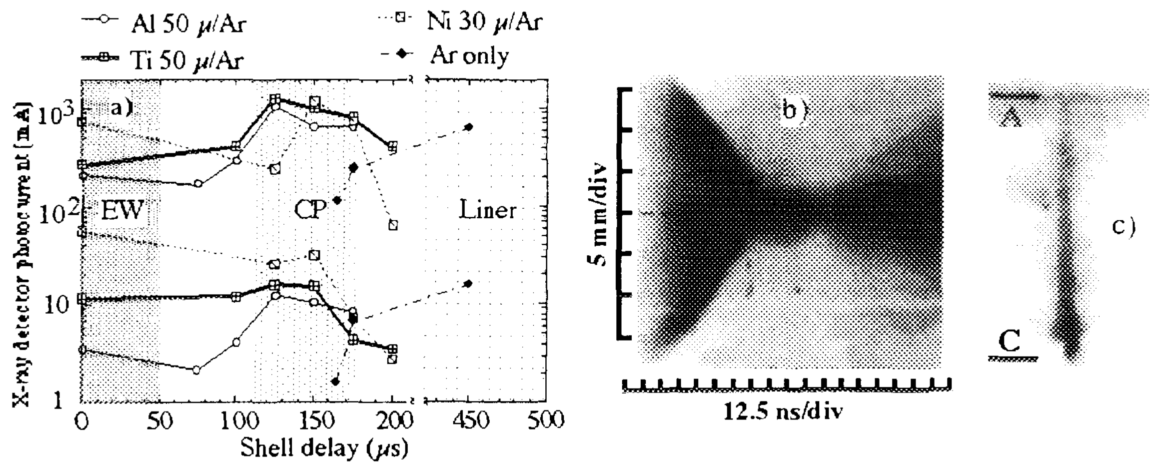

Fig. 9

Fig. 9. (a) Maximum responses of two X-ray channels sensitive to the radiation in 2-5 keV (upper curve) and 5-20 keV (lower curve) photon energy regions. Best shots for C-pinch, exploding wire and liner configurations for different time delays of the gas injection (τ = 0 corresponds to the wire only shots).
(b) Typical streak picture of the C-pinch. (c) Typical time-integrated image on HP-5 film behind a 200 μ-diameter pin-hole and 20 μ Al filter.

The internal plasma shell and the axial core were considered as a C-pinch. Initial plasma density was controlled by varying the delay, τ, of the generator current start with respect to the internal shell injection. The optimum τ were expected to be in the range τ = 50-250 μs., which corresponded to the shell mass m_L = 2-40 μg/cm.

Optimized C-pinch regimes were characterized by a narrow single-peak above-1 keV X-ray pulse, axial core preradiation on the streak photos (Fig. 9b), and tight homogeneous image of the PRS on time-integrated X-ray pictures (Fig. 9c). Besides, for all the axial core materials used a higher X-ray power was achieved in this scheme, when compared with "pure" or near-liner regimes as well as the EW regime. Optimum delays, τ = 100-200 μs (mean initial density in the range 5×10^{15}-5×10^{16} cm^{-3}), correlated well with the model predictions. Shots from the central region on the diagram of Fig. 9a correspond in the experiment to the clearly apparent C-pinch effect (better spatial and temporal homogeneity of the source, etc).

Time-resolved X-ray spectrum in the optimized Ar/Ni C-pinch indicated also successful heating of the Ni plasma. Intense radiating Ni K-shell lines and practical absence of the Ar K-shell radiation in the spectrum indicate efficient energy transfer from the external plasma layers towards the axial core.

CONCLUSIONS

In conclusion, this paper overviews several aspects of the POS and Z-pinch physics which would have a considerable impact to the Syrinx project. These two elements are considered to be the most critical in the project and require further detail scientific examination. In particular, reliable scalings of the conduction and opening time, as well as of the POS resistance are required to scale the POS operation to higher power levels. Analysis of MAG-1 data proposes already some scaling relations for the conduction and opening phases. Plasma density measurements on GIT-8 reveal some new features of the POS resistance formation in high-density regime of the switch operation. Our Z-pinch study allowed us to introduce a concept of the Composite Pinch. First attempts on the modeling of this scheme were based on the assumption of disruptions of the current in the C-pinch plasma. Controlled plasma instabilities are shown to lead to a staged efficient current transfer from the external plasma layers towards the internal radiating core. Proper choice of initial parameters allowed higher radiated power, easier X-radiation spectrum control, spatial and temporal homogeneity of the final collapse. Finally, our POS and Z-pinch research programs are closely connected; both of them are oriented to better understanding of the current transfer mechanisms in complex IES plasma systems.

ACKNOWLEDGMENTS

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[1] R.B.Spielman, in *Proceedings of the Ninth International Conference on High-Power Particle Beams*, edited by D.Mosher and G.Cooperstein (NTIS, Washington, 1992), Vol. 3, p. 2002.

[2] L.Véron, B.Etlicher, A.S.Chuvatin, C.Rouillé, J.P.Stephan, *IEEE Trans. Plasma Sci.* **21**, 529 (1993).

[3] A.S.Chuvatin, L.Véron, N.S.Edison, B.Etlicher, C.Rouillé, J.P.Stephan, H.Lamain, and P.Avray, PMI 2621, Nov. 1992; see also *Bull. Amer. Phys. Soc.* **37**, 1565 (1992).

[4] A.S.Chuvatin, B.Etlicher, N.S.Edison, and C.Rouillé, *Rev. Sci. Instrum.* **64**, 2267 (1993).

[5] A.S.Chuvatin and B.Etlicher, *Phys. Rev. Lett.* **74**, 2965 (1995).

[6] A.S.Kingsep, K.V.Chukbar, and V.V.Yan'kov, in *Reviews of Plasma Physics*, edited by B.Kadomtsev (Consultants Bureau, NY, 1990), Vol. 16, p. 243.

[7] A.V.Gordeev, A.S.Kingsep, and L.I.Rudakov, *Physics Reports* **243**, 215 (1994)

[8] A.S.Kingsep, Yu.V.Mokhov, and K.V.Chukbar, *Sov. J. Plasma Phys.* **10**, 495 (1984).

[9] A.S.Chuvatin, *Ph.D.thesis*, PMI-2874, Ecole Polytechnique, 1993.

[10] A.S.Chuvatin, L.I.Rudakov, and B.Etlicher, this conference proceedings, paper P-4-63.

[11] V.Frolov, A.Chuvatin, S.Semushin, and B.Etlicher, this conference proceedings, paper P-4-67.

[12] G.I. Dolgachev et al., *Sov. J. Plasma Phys.* **17** (10), 1171 (1991).

[13] A.Chuvatin, C.Rouillé, B.Etlicher, F.Bayol, A.Morell, A.Kim, S.Loginov, V.Kokshenev, and B.Kovalchuk, this conference proceedings, paper P-4-64.

[14] L.E.Aranchuk, A.S.Chuvatin, A.V.Gordeev, "Model for calculation of output characteristics of nanosecond REB generator with Plasma Opening Switch", *Eighth Int. Conf. on High-Power Particle Beams*, Novosibirsk, USSR, July 2-5, 1990.

[15] K.V.Chukbar and V.V.Yan'kov, *Sov. Phys. Tech. Phys.* **33**, 1293 (1988).

[16] A.S.Chuvatin, P.Choi, and B.Etlicher, *Phys. Rev. Lett.* **76**, 2282 (1996).

[17] A.Chuvatin, P.Choi, B.Etlicher, S.Semushin, C.Dumitrescu, M.Vié, F.Bayol, A.Morell, A.Shishlov, A.Fedyunin, R.Baksht, I.Datsko, A.Russkikh, B.Kovalchuk, A.Kim, V.Kokshenev, S.Loginov, and A.Bastrikov, in *Proceedings of the 10th International Pulsed Power Conference* , Albuquerque, NM, USA, July 10-13, 1995.