Equivalent Modeling of Microchannel Plate Framing Camera Gain Uniformity

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Abstract

In X-ray framing cameras, the gating pulse will be attenuated as it transmits along the microchannel plate (MCP) microstrip cathode, which affects the dynamic gain uniformity of the MCP. A full-wave electromagnetic attenuation model for gating pulse transmission on the MCP microstrip cathode was established to investigate dynamic gain uniformity. To improve computational efficiency, the porous MCP containing on the order of 10^7 microchannels was represented as an equivalent homogeneous medium with a frequency-dependent complex permittivity. For a Gaussian gating pulse with an amplitude of −2 kV and a full width at half maximum (FWHM) of 200 ps propagating along a 40 mm-long and 8 mm-wide microstrip, the simulated pulse decreased to −1.05 kV and the FWHM increased to 240 ps. As a result, the MCP gain decreased to 33% along the pulse transmission direction. An X-ray framing camera has been developed to verify the correctness of the theoretical model. The MCP dynamic gain uniformity was measured using an ultraviolet laser with a FWHM of 6.5 ns, which demonstrated that the gain dropped to 27%, consistent with the simulation result. An error-correction model was proposed, which reduced the normalized root mean square error from 4.72% for the original simulation to 2.58%.

Full Text

Preamble

Equivalent Modeling of Microchannel Plate Framing Camera Gain Uniformity∗

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Key Laboratory of Optoelectronic Devices and Systems of Education and Guangdong Province, Shenzhen Key Laboratory of Photonics and Biophotonics, Shenzhen Key Laboratory of Ultrafast Laser Micro/Nano Manufacturing, College of Physics and Optoelectronic Engineering, Shenzhen University, Shenzhen 518060, China In X-ray framing cameras, the gating pulse will be attenuated as it transmits along the microchannel plate (MCP) microstrip cathode, which affects the dynamic gain uniformity of the MCP. A full-wave electromagnetic attenuation model for gating pulse transmission on the MCP microstrip cathode was established to investigate dynamic gain uniformity. To improve computational efficiency, the porous MCP containing on the order of 107 microchannels was represented as an equivalent homogeneous medium with a frequency-dependent complex permittivity. For a Gaussian gating pulse with an amplitude of −2 kV and a full width at half maximum (FWHM) of 200 ps propagating along a 40 mm-long and 8 mm-wide microstrip, the simulated pulse decreased to −1.05 kV and the FWHM increased to 240 ps. As a result, the MCP gain decreased to 33% along the pulse transmission direction. An X-ray framing camera has been developed to verify the correctness of the theoretical model. The MCP dynamic gain uniformity was measured using an ultraviolet laser with a FWHM of 6.5 ns, which demonstrated that the gain dropped to 27%, consistent with the simulation result. An error-correction model was proposed, which reduced the normalized root mean square error from 4.72% for the original simulation to 2.58%.

Keywords

High energy density physics, Inertial confinement fusion, X-ray diagnostics, Ultrafast diagnostics, Framing imaging

INTRODUCTION

transmitting a high-voltage narrow gating pulse on the MCP microstrip cathode, a temporal resolution of tens of picosec25 onds and high electron gain can be achieved. However, the 26 amplitude of the gating pulse continuously decreases during 27 transmission along the MCP microstrip cathode, which sig28 nificantly affects the MCP gain and leads to a gradual de29 crease in the image intensity of the microstrip cathode along 30 the pulse transmission direction.

This is the major source 31 of systematic uncertainty in diagnostics.

Although hybrid 32 CMOS (hCMOS) detectors typically exhibit more uniform 33 and stable pixel responses following calibration and flat-field 34 correction, their highest temporal resolution is 1 ns [19–22]. 35 In contrast, the MCP-based technologies have achieved tem36 poral resolutions as high as 60 ps. Consequently, MCP-based 37 systems remain indispensable, and their gain characteristics 38 necessitate meticulous optimization.

Inertial confinement fusion (ICF), magnetic confinement fusion (MCF), and Z-pinch experiments produce optically 4 opaque states of matter that evolve on micrometer spatial 5 scales and sub-nanosecond time scales. High spatial and tem6 poral resolution X-ray imagers are required to diagnose such 7 states [1–8]. Microchannel plate (MCP) gated X-ray framing 8 cameras with high temporal resolution and two-dimensional 9 spatial imaging capabilities are widely used in those fields [9–10 11]. As the core of these systems, the MCP imager deter11 mines the temporal resolution, spatial resolution, and gain 12 uniformity of the diagnostic [12–14].

A typical MCP im13 ager comprises a microstrip cathode, an MCP, and a phosphor 14 screen. The microstrip cathode converts a two-dimensional 15 X-ray image into an electron image. During the gating pe16 riod, the MCP multiplies and outputs the electrons. The elec17 tron image emitted from the MCP is accelerated by the phos18 phor screen voltage and bombards the phosphor to form a vis19 ible image [15–18]. The MCP exhibits a high gain, and its 20 gain is approximately proportional to the 7 to 9th power of 21 the operating voltage, which means a modest variation in gat22 ing voltage can significantly lead to gain nonuniformity. By

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The MCP gain inconsistency, which is caused by the microstrip cathode transmission attenuation, affects the mea41 surement accuracy of the ICF implosion experiment data cap42 tured by the camera. The attenuation of the gating pulse has 43 been analyzed using transmission-line theory and distributed 44 equivalent-circuit models.

These models are computation45 ally efficient and offer physical insight into resistive and di46 electric losses.

However, their reliance on quasi-TEM as47 sumptions limits their validity for broadband sub-nanosecond 48 pulses, electrically long structures, strong dispersion, reflec49 tions and structural nonuniformities [23, 24]. By contrast, 50 full-wave electromagnetic methods solve Maxwell’ s equa51 tions directly without invoking quasi-TEM or quasi-static ap52 proximations, which can capture broadband propagation, dis53 persion, coupling, reflections, and distributed loss in a self54 consistent manner. The finite integration technique (FIT) pro55 vides a general spatial discretization framework for electro56 magnetic problems from static fields to high-frequency appli57 cations in both the time and frequency domains. It is partic39 ularly suitable for broadband transient analysis because it is 112 pulse propagation and field variation. For pulse-transmission based on the integral form of Maxwell' s equations and pre- 113 analysis, the porous MCP was homogenized as an equiva60 serves conservation laws at the discrete level [25–28]. Com- 114 lent circular disk with effective material parameters. This ap61 pared with reduced-order equivalent-circuit models, FIT pro- 115 proximation is physically justified because the dense air-filled 62 vides a more complete description of pulse propagation in 116 microchannel array modifies the effective dielectric environ63 MCP microstrip structures, especially for broadband excita- 117 ment and redistributes electric-field energy between the solid 64 tion and electrically long transmission paths. In 2005, Mc- 118 matrix and the pore regions. Explicit pore-resolved modeling 65 Carville et al. showed that the gating-pulse voltage on MCP 119 is feasible in principle, but for macroscopic pulse-attenuation 66 microstrip cathodes decays approximately exponentially with 120 analysis, the equivalent homogeneous-medium treatment is 67 propagation distance, and several strategies have been pro- 121 more appropriate and greatly reduces modeling and compu68 posed to mitigate attenuation-induced gain nonuniformity, 122 tational cost. 69 including spatial bias compensation, impedance matching, 70 reflection compensation, and microstrip-geometry optimiza71 tion [29]. In 2019, Cai et al. reported a framing camera with a 72 20 mm-wide MCP microstrip cathode for a grating spectrom73 eter and improved gain uniformity by simultaneously driving 74 the cathode with four gating pulses [30]. Measurements on 75 the SG-III laser facility showed that the MCP gain decreased 76 to about 30% of its initial value along the pulse-propagation 77 direction.

In this work, the gain uniformity of an MCP-gated framFig. 1 [Figure 1: see original paper]. Structure of the MCP microstrip cathode. 79 ing imager was investigated to improve the measurement ac80 curacy. A full-wave transmission-attenuation model of the 81 MCP microstrip cathode was established, and the resulting 123 The full-wave electromagnetic response of the proposed 82 gain nonuniformity caused by pulse attenuation was analyzed 124 structure was computed with the FIT-based transient solver 83 using FIT. To validate the proposed model, an X-ray fram- 125 in CST Microwave Studio. In this method, the integral form 84 ing camera was developed and the MCP gain uniformity was 126 of Maxwell' s equations is discretized on a primary grid and 85 measured experimentally. 127 its orthogonal dual grid. Electric grid voltages e and magnetic 128 facet fluxes b are defined on the primary grid, whereas mag129 netic grid voltages h and dielectric facet fluxes d are defined II. TRANSMISSION ATTENUATION MODEL OF THE 130 on the dual grid. This discretization yields the matrix form,

MCP MICROSTRIP CATHODE

Geometrical Model and Full-Wave Formulation

e h=− d d+j ed = q Sb = 0 Ce = −

A three-dimensional electromagnetic model of the MCP 131 microstrip cathode was established in CST Microwave Stu91 dio, as shown in Fig. 1. Two microstrip cathodes were formed 92 on the MCP input surface to convert incident X-rays into pho93 toelectrons and transmit gating pulses. The MCP had a thickEq.1 is known as the Maxwell' s Grid Equations (MGEs). 94 ness of 0.5 mm and a diameter of 56 mm. The practical MCP 132 topological matrices C and C̃ are the discrete counter95 had a nominal pore diameter of 12 µm and a bias angle of 96 6 , but these pore-scale features were not explicitly resolved 134 parts of the analytical curl operator on the primary and dual 97 in the electromagnetic model. Each microstrip cathode con- 135 grids, while S and S̃ are the corresponding discrete diver98 sisted of a 400 nm copper layer coated with 200 nm of gold, 136 gence operators. The material and metric information is in99 with a strip width of 8 mm and a gap of 3 mm between ad- 137 troduced through the constitutive matrices, 100 jacent strips. The copper and gold films with the same thick101 ness were evaporated onto the entire MCP output surface to d = Mϵ e 102 serve as a ground plane. A 60 mm-long impedance taper was b = Mµ h 103 fabricated on a polytetrafluoroethylene printed-circuit board 138 104 (ϵr = 2.2) and was connected to the MCP microstrip cathode j = Mσ e + js 105 by a gold foil to achieve impedance matching. The gating 106 pulse was launched from a waveguide port and delivered to 139 where Mϵ , Mµ , and Mσ depend on the material properties 107 the cathode through the taper. An open boundary condition 140 and the local mesh geometry. 108 was applied in all directions to emulate an unbounded do- 141 In the transient solver, the resulting semi-discrete equations 109 main and suppress spurious boundary reflections. A locally 142 are advanced in time using an explicit leap-frog scheme, in 110 refined hexahedral mesh was employed. The conductor and 143 which electric and magnetic quantities are staggered tempo111 the taper-to-cathode regions were further refined to resolve 144 rally. The representative update form can be expressed as,

was chosen by balancing fitting accuracy against model compactness. This avoids unnecessary pole contributions while e M−1 bn + jn + ∆t M−1 195 retaining the essential dielectric-dispersion behavior. To pre(3) 196 serve a clear physical basis for fitting, the initial reference bn+1 = bn − ∆t Cen+ 2 197 condition was estimated from the known structural charac146 This time-marching scheme is conditionally stable, so 198 teristics of the MCP, including the pore diameter, pore pitch, 199 bias angle, dielectric constant of the original substrate, and 147 the time step ∆t must satisfy the Courant-Friedrichs-Lewy 200 open-area ratio. These parameters provide an initial estimate 148 (CFL) criterion. The minimum mesh cell size therefore sets 201 of the equivalent dielectric environment of the porous MCP 149 the maximum admissible time step and has a strong impact 202 through effective-medium considerations, thereby constrain150 on the total computational cost. To improve the representa203 ing the fitting. The resulting dielectric-loss model is therefore 151 tion of curved and thin conducting features without exces204 a frequency-dependent equivalent dielectric description con152 sive mesh refinement, the Perfect Boundary Approximation 205 strained by the known MCP structure. 153 (PBA) and

Thin Sheet Technique (TST) are employed [31–The pulse attenuation along the MCP microstrip is de154 33]. This techniques can enhance both accuracy and compu- 206 207 scribed through the complex propagation constant. The re155 tational efficiency for complex microstrip configurations. 208 lationship between the amplitude V (x) of the gating pulse 209 and the transmission distance x is,

n+ 12

Frequency-Dependent Dielectric and Loss Mechanisms

n− 12

V (x) = V (0)e−$\alpha(\omega)$x e−j$\beta(\omega)$x . For physical interpretation of the attenuation mechanisms, 210 158 transmission-line theory is employed only as an auxiliary 211 where α and β denote the attenuation and phase constants. 159 framework, while the full-wave structural response is ob212 For broadband transient pulses, unequal attenuation of dif160 tained using FIT. The attenuation of the gating pulse may 213 ferent spectral components alters the pulse amplitude and 161 arise from dielectric, conductor, and magnetic losses. Mag214 shape during propagation. The MCP is therefore driven by a 162 netic loss is neglected in the present structure because both 215 position-dependent voltage, and the corresponding local gain 163 the MCP substrate and the surrounding media are nonmag216 can be approximated by, 164 netic. Conductor loss is included through the finite conduc165 tivity of the metallic electrodes, but it is not expected to dom166 inate because the electrodes are highly conductive. In conn G(x) = C [V (x)] . 167 trast, the porous MCP alters the effective dielectric environ168 ment and changes how electric-field energy is distributed be169 tween the solid matrix and the pore regions.

As a result, 218 where C is the gain constant and n is the number of the MCP 219 dynodes, typically in the range of 7–9. The resulting volt170 dielectric loss becomes particularly important in the present 220 age variation therefore produces spatial nonuniformity in the 171 structure. Quantitatively, dielectric attenuation generally in221 MCP gain. 172 creases approximately with frequency, whereas conductor at173 tenuation typically follows a square-root frequency depen174 dence because of the skin effect. Accordingly, magnetic loss III. SIMULATION RESULTS AND ANALYSIS 175 is neglected, conductor loss is treated as a secondary contri- 222 176 bution, and dielectric loss is taken as the dominant attenuation 177 mechanism.

The calculated S-parameters of the MCP microstrip cath178 To characterize this attenuation behavior, a frequency- 224 ode are shown in Fig. 2 Figure 2: see original paper. The transmission coefficient 179 dependent dielectric model is required. The loss tangent is 225 S 21 decreases with increasing frequency, which indicates a 180 defined as, 226 broadband attenuation and a stronger suppression of higher227 frequency components. These components contribute to the 228 sharp leading and trailing edges of the gating pulse. Their Im$\{\epsilon(\omega)\}$ tan $\delta(\omega)$ = (4) 229 preferential attenuation therefore leads to pulse-peak reducRe$\{\epsilon(\omega)\}$ 230 tion and temporal broadening during propagation. The reflec182 To describe the dielectric response over a broad frequency 231 tion coefficient S11 also shows noticeable oscillations, which 183 range, the pole-zero dispersion model was employed un- 232 suggests imperfect impedance matching and partial reflec184 der physically prescribed fitting constraints. In this model, 233 tions. Pulse propagation in the MCP microstrip cathode is 185 the relative permittivity and loss tangent were specified at a 234 therefore determined by the combined action of distributed 186 reference frequency f0 , thereby anchoring the dielectric re- 235 attenuation and reflection-induced waveform distortion. Ow187 sponse at a physically meaningful operating point. To en- 236 ing to structural symmetry, the corresponding S22 and S12 188 sure broadband consistency, the fitting band was selected to 237 responses are similar and are omitted for brevity. 189 extend beyond the dominant spectral range of the excitation 238 The input and output waveforms of the MCP imager are 190 pulse.

Logarithmic sampling was adopted to provide ade- 239 compared in Fig. 2(b). A Gaussian gating pulse with a peak 191 quate representation of both the low- and high-frequency re- 240 amplitude of −2 kV and an FWHM of 200 ps was applied 192 sponses. Within these prescribed constraints, the model order 241 at the input port. The gating pulse entered the input port,

passed through the input taper and the MCP microstrip cath- 263 1 mm intervals along each lineout. The sampled values from ode, and finally exited through the taper on the opposite side. 264 the five neighboring lineouts were then averaged to obtain the 244 After propagation, the pulse peak decreased to approximately 265 peak-voltage profile. 245 −1.5 kV, which is about 75% of its input value. The out- 266 Under a Gaussian excitation with an amplitude of −2 kV 246 put waveform also exhibited a pulse broadening (FWHM = 267 and an FWHM of 200 ps, the propagation time of gating pulse 247 278 ps), and noticeable distortion. 268 on 40 mm microstrip cathode was 220 ps, yielding a pulse 269 propagation velocity of approximately 1.8 × 10 m/s. In ad270 dition, the pulse peak decreased to about 88% of its initial 271 value, while the FWHM increased from 200 ps to approxi272 mately 240 ps. Shown in Fig. 3 Figure 3: see original paper, the waveform exhibited 273 noticeable ringing and a slight recovery near the output end. 274 This indicates that the transmitted and reflected components 275 overlapped between the microstrip cathode and the output 276 impedance taper. These results show that the gating pulse 277 undergoes coupled attenuation and waveform evolution.

(b) Waveforms of the gating pulse for the input and output sides of the MCP imager, the input amplitude is −2 kV, and the output amplitude is −1.5 kV.

The effective gating area was 40 mm at the center of the microstrip. For subsequent positional characterization, the in250 put end of the effective gating region on the upper microstrip 251 line was defined as x = 0, and the bottom edge of the same 252 microstrip line was taken as y = 0. To quantify the voltage microstrip cathode, 0 mm, 20 mm, 35 mm, and 40 mm on the mi253 evolution of the gating pulse, voltage monitors were placed crostrip cathode from left to right, (b) The relationship between the 254 every 5 mm on the microstrip.

For the x direction analyamplitude of the pulse and the transmission distance on the MCP 255 sis, the peak voltage at each sample position was obtained microstrip cathode. 256 by averaging five neighboring lineouts at y = 3, 3.5, 4, 4.5, 257 5 mm. This averaging reduced local numerical fluctuations 258 while remaining close to the microstrip centerline to preserve 278 Based on the peak-voltage distributions, the corresponding 259 the attenuation trend. To evaluate the y direction voltage dis- 279 MCP gain could be estimated from the power-law relation 260 tribution, five neighboring lineouts were selected at position 280 by taking n = 8. The spatial variation of gain followed the 261 x = 20 mm, namely at x = 19, 19.5, 20, 20.5, and 21 mm. 281 same overall trend as the voltage distribution, but with much 262 The peak voltage was sampled across the microstrip width at 282 stronger nonuniformity.

The simulated gain distributions parallel and perpendicu- 306 on pulse propagation. lar to the pulse-transmission direction are shown in Fig. 4 [Figure 4: see original paper]. 285 The MCP gain decreased with increasing transmission disIV. EXPERIMENTAL RESULTS AND ANALYSIS 286 tance and reached its minimum at x = 35 mm, which fell to 307 287 about 33% of its maximum. At x = 40 mm, however, the gain 288 rose slightly to approximately 39% of the maximum. This lo- 308 A. Measurement Setup and Results 289 cal recovery was attributed to pulse reflection near the output 290 end. According to Fig. 4(b), the MCP gain curve perpen309 An X-ray framing camera consisting of an MCP imager 291 dicular to the pulse transmission direction was symmetrically 310 and a gating-pulse generator was developed in this work, as 292 distributed around the midpoint of the microstrip cathode at 311 shown in Fig. 5 [Figure 5: see original paper].

The MCP imager was composed of the 293 4 mm, and the gain variation was within 3%. The results indi312 impedance taper, the microstrip cathode evaporated on the 294 cate that the dominant gain nonuniformity is introduced along 313 MCP input surface, the MCP, and the phosphor screen fab295 the pulse-transmission direction, whereas the transverse vari314 ricated on a fiber optic panel. Its function was to sample and 296 ation is comparatively weak. 315 multiply the photoelectrons to achieve a high spatiotemporal 316 resolution. A circular MCP was used in this work with an 317 outer diameter of 56 mm and a thickness of 0.5 mm. The 318 channel diameter was 12 µm, the bias angle was 6 , and 319 the center-to-center spacing between adjacent channels was 320 14 µm. Two microstrip cathodes were deposited on the MCP 321 input surface, each consisting of a 400 nm-thick copper layer 322 coated with 200 nm of gold. Each strip had a width of 8 mm, 323 and the gap between the two cathodes was 3 mm. The entire 324 MCP output surface was coated with copper and gold films of 325 the same thicknesses to serve as the ground plane. The dis326 tance between the MCP and the phosphor screen was 0.5 mm, 327 and the CCD was directly coupled to the phosphor screen to 328 record the visible image.

gain of MCP along the gating pulse propagation direction, (b) Normalized gain of MCP in the transverse direction.

It is worth mentioning that a practical MCP combines micrometer-scale pores with centimeter-scale device will 299 make pore-resolved full-wave simulation computationally exWaveforms of the gating pulse at the input and output ports of the 300 pensive. A reduced 100-pore model confirmed that explicit MCP imager. 301 pore resolution requires much finer meshing and longer com302 putation. Since this study focuses on device-scale pulse atten303 uation rather than local fields of individual pores, the homog- 329 The ultrafast electrical pulse was key to the MCP gating 304 enized treatment provides a physically justified and computa- 330 framing technology because it determined the temporal res305 tionally efficient representation of the effect porous structure 331 olution of the camera [34–36]. The X-ray framing camera

required a gating pulse with an amplitude of over a kilo- 390 ized image along the directions parallel and perpendicular to volt and widths of hundreds or even tens of picoseconds to 391 the pulse-transmission direction. To reduce the influence of 334 achieve a sufficient gain and high temporal resolution. An 392 statistical fluctuation and local imaging noise, the gain pro335 avalanche transistor was an ideal device for ultrafast pulse 393 files were obtained by averaging multiple neighboring line336 circuit due to its high-speed switching characteristic.

The 394 outs. First, establish a coordinate axis the same as in Section 337 gating pulse generator was composed of an avalanche tran- 395 3. For the x direction, the gain was obtained by averaging 338 sistor circuit and a diode pulse shaping circuit. An electrical 396 five 40 mm-long lineouts at y = 3, 3.5, 4, 4.5, and 5 mm. The 339 signal with 5 V and 1 Hz was used to trigger the avalanche 397 y direction gain distribution was obtained by selecting five 340 transistor circuit. Then, the avalanche transistor circuit gen- 398 40 mm-long lineouts at position x = 19, 19.5, 20, 20.5, and 341 erated a high-voltage pulse with an amplitude of 5 kV and 399 21 mm. In this way, the extracted profiles capture the macro342 a FWHM of 6 ns, which then drove the diode pulse shaping 400 scopic gain distribution of the MCP imager while suppressing 343 circuit to produce a short high-voltage pulse. At the begin- 401 local pixel-level noise. 344 ning, part of the fast ramp high-voltage pulse was coupled 345 through the capacitor to the output. As the voltage across the 346 diode increased, avalanche breakdown occurred in the diode, 347 resulting in a sharp falling edge. The pulse was then shaped 348 by the combined effect of the capacitor and the high-pass fil349 ter at the output terminal. Then, an MCP gating pulse with 350 an amplitude of −2 kV and a FWHM of 200 ps was gener351 ated, as the red curve shown in Fig. 5(c). The gating pulse 352 was transmitted through a coaxial cable to the SMA connec353 tor of the MCP imager and then entered the impedance taper 354 line. Subsequently, it propagated along the MCP microstrip 355 cathode for electron gating, and then to the impedance ta356 per line at the other end. Finally, the gating pulse exited the 357 MCP imager from another SMA connector on the other end. 358 Reflection and attenuation occurred during the transmission 359 process, which caused the amplitude of the gating pulse to 360 decrease along the transmission direction. The output wave361 form of the MCP imager is shown by the blue curve in Fig. 5. 362 The amplitude decreased to about 70%, which was consistent 363 with the 75% attenuation simulation result shown in Fig. 2.

The gain uniformity of the X-ray framing camera was mea365 sured by using a nanosecond ultraviolet laser, as depicted in 366 Fig. 6 Figure 6: see original paper. The 266 nm laser beam was expanded and illumi367 nates the MCP microstrip cathode to excite photoelectrons. 368 The 800 nm laser was irradiated onto the PIN detector to gen369 erate an electrical signal, which passed through the delay cir370 cuit and then triggered the generator to produce the MCP gat371 ing pulses. The delay circuit could synchronize the arrival 372 time of 266 nm laser and gating pulse on the MCP microstrip 373 cathode to generate the gating images. A PIN detector was setup, (b) Waveform of the nanosecond ultraviolet laser pulse. 374 used to measure the waveform of the 266 nm laser and shown 375 in Fig. 6(b). The laser pulse width was approximately 6.5 ns 376 with a flat-top of approximately 3.2 ns. The gating pulse was The corresponding normalized gain curves are shown in 377 synchronized in the central region of the 3.2 ns flat-top by 403 Fig. 7 Figure 7: see original paper and Fig. 7(e). Along the pulse-transmission direc378 controlling the timing of the delay circuit. 404 tion, the MCP gain reached its minimum at 35 mm, where To characterize the gain distribution of the MCP imager, 405 it decreased to about 27% of the maximum value. A raising 380 both static and gated images of the microstrip cathode were 406 MCP gain of 32% at 40 mm, which was due to the pulse re381 recorded. While the MCP was only loaded with a bias volt- 407 flection and superposition. In the y direction, the normalized 382 age of −700 V, the static image of the microstrip cathode was 408 MCP gain varied within 5%. Both experiment and simulation 383 obtained and shown in Fig. 7(a). While a gating pulse over- 409 show a minimum near 35 mm, followed by a slight recovery 384 lapping a bias voltage of −400 V was applied to MCP, the 410 near the output end. This trend suggested that the observed 385 gating image of the microstrip cathode is shown in Fig. 7(b). 411 MCP gain nonuniformity was mainly caused by pulse atten386 The static image was utilized to normalize the gating image 412 uation and local pulse reflection. The measured gain distri387 to eliminate the impact of light pulse non-uniformity, and the 413 butions were in good agreement with the simulated results, 388 normalization gating image is shown in Fig. 7(c). 414 which validated the correctness of the gating pulse propaga389 Quantitative gain profiles were extracted from the normal- 415 tion attenuation and the MCP gain model.

voltage of −400 V applied to MCP, the gating pulse transmits from left to right, (c) Normalization gating image, (d) Normalized dynamic MCP gain along the gating pulse transmission direction, (e) Normalized dynamic MCP gain for the transverse direction.

Error Analysiss

Isim,pk (x) [Vpk (x)] . A clear distinction between dominant error sources and

418 secondary uncertainties under the present conditions is im452 where Vpk (x) is the local peak voltage. This indicates that 419 portant for quantitative analysis of the discrepancy between 453 the measured data is determined by the temporal integral of 420 simulation and experiment. The residual nonuniformity of 454 the nonlinear gain response rather than by the pulse peak 421 the ultraviolet illumination was largely removed by normal455 alone. Here, we define a corrected simulated light intensity, 422 ization with the static image. While the pixel-level statistical 423 fluctuation and local CCD noise were suppressed by averag 424 ing multiple neighboring lineouts. Trigger jitter is also ex Isim,corr (x) = C κn (x) [Vpk (x)] eff 425 pected to be secondary, since MCP framing-camera gating [Veff (x; t)] eff dtgate 426 pulses exhibit timing jitter of only several tens of picosec [Vpk (x)] 427 onds, whereas the ultraviolet laser used for gain-uniformity 428 measurements has a pulse width of about 6.5 ns and a flat457 where C is a normalization-related scaling constant and 429 top duration of approximately 3.2 ns. With the gating pulse 458 κn (x) is the gating-integration factor. It should also be noted 430 synchronized to the central region of this flat-top, the residual 459 that MCP gain is threshold-related, so only the portion of the 431 jitter is unlikely to dominate the observed spatial gain dis460 local gating waveform that enters the gain-on regime con432 crepancy.

The dominant discrepancy mainly arises from two factors. 461 tributes to the recorded signal. However, the present compar462 ison is based on normalized spatial profiles, introducing an 434 The first is the mismatch between the measured and simu463 explicit threshold parameter would add unconstrained model 435 lated observables: the CCD records the optical signal inte464 freedom. The threshold effect is therefore treated implicitly 436 grated over the effective gating window, whereas the simula465 in the effective correction framework. 437 tion provides the local transient gating waveform and the cor466 When the local propagated waveform remains approxi438 responding peak-voltage evolution. A direct comparison is 467 mately single-peaked, the gating-integration factor can be 439 therefore incomplete. The second source is the number of the 468 simplified under a Gaussian-pulse approximation.

In this 440 MCP dynodes. In the simulation, a representative value 8 was 469 case, raising the local gating waveform to the power neff re441 adopted, whereas the effective exponent in the experiment 470 duces its effective width by a factor of 1/ neff . The cor442 may differ from this nominal value for the device-specific 471 responding temporal integral is therefore proportional to the 443 gain characteristics, operating bias, and local multiplication 472 local pulse width and inversely proportional to neff , which 444 conditions. 473 is, The measured light intensity at position x and the corre446 sponding time t should be expressed as, τFWHM (x) κn (x) √ Imeas (x) [Veff (x; t)] eff dtgate . 475 Where τFWHM (x) is the FWHM of the local pulse. This re476 lation shows that the correction is determined by the local 448 where Veff (x; t) is the local effective gating voltage, and neff 477 temporal broadening and the nonlinear gain exponent. 449 is the effective gain-voltage exponent. By contrast, the peak- 478 The discrepancy can be quantified by the normalized root 450 based gain model used in Section 3 is, 479 mean square error (NRMSE),

mainly near the output end, where waveform distortion and reflection effects become more pronounced. These results in498 dicate that the combined FWHM- and exponent-dependent (11) 499 correction captures the main discrepancy.

I^sim,corr (xi) − I^exp (xi) . NRMSE = t N i=1

where N is the number of sampled spatial positions, I^sim,corr (xi) is the normalized corrected simulated intensity, 483 and Iexp (xi) is the normalized experimental intensity.

V. CONCLUSION The proposed correction model was applied to the x direc- 500 485 tion gain data, using the NRMSE as the criterion. The sim486 ulated local pulse FWHM was included to account for tem501 The dynamic MCP gain characteristics were investigated. 487 poral integration and the effective gain-voltage exponent was 502 A full-wave transmission-attenuation model of the MCP mi488 determined by parameter sweep. The minimum NRMSE was 503 crostrip cathode was established. A practical MCP contains 489 obtained at nef f = 10.16, reducing the error from 4.72% for 504 on the order of 10 microchannels. Explicit pore-resolved 490 the original simulation to 2.58%. 505 modeling would be computationally expensive. In the present 506 model, the porous MCP was treated as an equivalent homo507 geneous medium with a frequency-dependent dielectric-loss 508 description. The simulations showed that a −2 kV, 200 ps 509 Gaussian gating pulse decreased to about 88% of its initial 510 peak after propagating along a 40 mm MCP microstrip cath511 ode. Owing to the strongly nonlinear gain-voltage relation of 512 the MCP, this voltage attenuation led to a longitudinal gain re513 duction to about 33% of the maximum value, while the trans514 verse variation remained within 3%.

An X-ray framing camera was developed, and the dynamic MCP gain uniformity was measured using an ultraviolet laser 517 with a pulse width of 6.5 ns. The experimental results demon518 strated that the gain decreased to about 27% along the pulse519 propagation direction and varied within 5% in the trans- verse 520 direction. Both simulation and experiment showed a local 522 and superposition, thereby enhancing the MCP gain in this profiles relative to the experiment in x direction. 523 region. Furthermore, an error-analysis frame- work was pro524 posed to account for the temporal integration effect and the To further illustrate the spatial distribution of the discrep525 uncertainty in the gain-voltage exponent. This reduced the 492 ancy, the absolute residual error, defined as 526 NRMSE between simulation and experiment from 4.72% to 527 2.58%.

Eabs (x) = Isim,corr/org (x) − Iexp (x) × 100%. (12) 528 The equivalent modeling can be extended to the design and

529 optimization of MCP detectors with high spatiotemporal resFig. 8 [Figure 8: see original paper] shows the spatial distribution of the residual error 530 olu- tions, such as X-ray streak cameras, photomultiplier tubes, 495 after correction.

The remaining discrepancy is concentrated 531 and so on.

[1] A. B. Zylstra, O. A. Hurricane, D. A. Callahan, et al., Burn- 543 14, 5782 (2023). doi: 10.1038/s41467-023-41477-2 ing plasma achieved in inertial fusion. Nature. 601, 542–548 544 [4] S. Jiang, F. Wang, Y. Ding, et al., Experimental progress of (2022). doi: 10.1038/s41586-021-04281-w inertial confinement fusion based at the ShenGuang-III laser [2] Y. Bai, Y. Jiang, W. Lv, et al., Reduction of Dynamic 546 facility in China. Nuclear Fusion. 59, 032006 (2019). doi:

Spatial Distortion of Miniaturized Streak Tube Using De- 547 10.1088/1741-4326/aabdb6 flection Compensation Technique. IEEE Transactions on 548 [5] S. Ding, A. M. Garofalo, H. Q. Wang, et al., A high-density Instrumentation and Measurement. 73, 1–7 (2024). doi: 549 and high-confinement tokamak plasma regime for fusion en10.1109/TIM.2024.3485443 ergy. Nature. 629, 555–560 (2024). doi: 10.1038/s41586-024[3] J. Yan, J. Li, X. T. He, et al., Experimental confirmation of 551 driving pressure boosting and smoothing for hybrid-drive iner- 552 [6] C. F. Maggi, D. Abate, N. Abid, et al., Overview of T and Dtial fusion at the 100-kJ laser facility. Nature Communications. 553 T results in JET with ITER-like wall. Nuclear Fusion. 64(11),

112012 (2024). doi: 10.1088/1741-4326/ad3e16 10.1063/1.4963956 [7] X. Gong, Y. T. Song, B. N. Wan, et al., Overview of recent 614 [23] H. Zhao, X. Liu, C. Chen, et al., Development and Test556 experimental results on the EAST tokamak. Nuclear Fusion. 615 ing of a Novel Microstrip Photocathode ICCD for Lunar Re557 64(11), 112013 (2024). doi: 10.1088/1741-4326/ad4270 mote Raman Detection. Sensors. 25(5), 1528 (2025). doi: [8] W. Lv, Y.-L. Bai, Y. Jiang, et al., Enhancing Temporal Uni- 617 10.3390/s25051528 formity in Pulse-Dilation Framing Camera Using Curved- 618 [24] M. C. Thomas, G. J. Yates, P. Zagarino, et al., Fast optical gat560 Dilation-Pulse. IEEE Transactions on Nuclear Science. 72(6), 619 ing using planar-lead MCPIIs and linear microstrip impedance 1843–1848 (2025). doi: 10.1109/TNS.2025.3569639 transformers. Proceedings of SPIE. 2273, 214–221 (1994). doi: [9] H. Z. Cai, Q. Y. Luo, K. X. Lin, et al., Ultrafast pulse-dilation 621 10.1117/12.189029 framing camera and its application for time-resolved X-ray di- 622 [25] T. Weiland, A discretization method for the solution of agnostic. Nuclear Science and Techniques. 35, 126 (2024). doi: 623 Maxwell' s equations for six-component fields. AEÜ Archiv für 10.1007/s41365-024-01408-2 Elektronik und Übertragungstechnik. 31, 116–120 (1977). 566 [10] J. S. Tian, Introduction to development of streak and framing 625 [26] T. Weiland, Time domain electromagnetic field computa567 cameras. High Power Laser and Particle Beams. 32, 112003 626 tion with finite difference methods. International Journal (2020). doi: 10.11884/HPLPB202032.200119 of Numerical Modelling: Electronic Networks, Devices 569 [11] H. Z. Cai, K. X. Lin, Q. Y. Luo, et al., Two-Dimensional Ultra- 628 and Fields. 9, 295–319 (1996). doi: 10.1002/(SICI)1099570 fast X-ray Imager for Inertial Confinement Fusion Diagnostics. 629 1204(199607)9:4¡295::AID-JNM240¿3.0.CO;2-8 Photonics. 9(5), 287 (2022). doi: 10.3390/photonics9050287 630 [27] B. Krietenstein, R. Schuhmann, P. Thoma, et al., The Per572 [12] W. Feng, X. Zhang, Y. L.

Li, et al., Progress in high time- and 631 fect Boundary Approximation technique facing the challenge space-resolving diagnostic technique for laser-driven inertial 632 of high precision field computation. Proc. of the XIX Inter574 confinement fusion. High Power Laser and Particle Beams. 32, 633 national Linear Accelerator Conference (LINAC' 98). Chicago, 112002 (2020). doi: 10.11884/HPLPB202032.200136 USA, 860-862 (1998). 576 [13] N. W. Liu, L. H. Chang, Z. F. Xiao, et al., Measur- 635 [28] T. Weiland, RF & microwave simulators—from component to ing gating time of gated image intensifier. High Power 636 system design. Proceedings of the European Microwave Week Laser and Particle Beams. 24(10), 2447-2450 (2012). doi: 637 (EuMW 2003). Vol. 2, 591-596 (2003). 10.3788/HPLPB20122410.2447 638 [29] McCarville T, Fulkerson S, Booth R, et al., Gated x-ray intensi580 [14] Y. Yang, B. L. Zhu, Y. S. Gou, et al., Sealed X-ray framing tube 639 fier for large format simultaneous imaging. Review of scientific with CsI photocathode to achieve high detection efficiency and 640 instruments. C 76, 10 (2005). doi: 10.1063/1.2090328 stability. High Power Laser and Particle Beams. 33, 092001 641 [30] Cai H, Deng P, Fu W, et al., X-ray imager with a 20 mm (2021). doi: 10.11884/HPLPB202133.210192 width microstrip line for the extreme ultraviolet spectrometer. 584 [15] M. J. Eckart, R. L. Hanks, J. D. Kilkenny, et al., Large- 643 IEEE Access. C 7, 98781-98785 (2019). doi: 10.1109/AC585 area 200-ps gated microchannel plate detector. Review 644 CESS.2019.2928422 of Scientific Instruments. 57(8), 2046-2048 (1986). doi: 645 [31] K. S. Yee, Numerical solution of initial boundary value prob587 10.1063/1.1138785 lems involving Maxwell' s equations in isotropic media. IEEE 588 [16] J. D. Kilkenny, P. Bell, R. Hanks, et al., High-speed gated x- 647 Transactions on Antennas and Propagation. 14(3), 302-307 ray imagers (invited). Review of Scientific Instruments. 59(8), 648 (1966). doi: 10.1109/TAP.1966.1138693 1793-1796 (1988). doi: 10.1063/1.1140115 649 [32] T. Weiland, Time domain electromagnetic field computa591 [17] W. Yang, Y. Bai, B. Liu, et al., Temporal resolution technology 650 tion with finite difference methods. International Journal of of a soft X-ray picosecond framing camera based on Chevron 651 Numerical Modelling: Electronic Networks, Devices and micro-channel plates gated in cascade. Nuclear Instruments 652 Fields. 9(4), 295-319 (1996). doi: 10.1002/(SICI)1099594 and Methods in Physics Research Section A. 608(2), 291-296 653 1204(199607)9:4¡295::AID-JNM240¿3.0.CO;2-8 (2009). doi: 10.1016/j.nima.2009.06.110 654 [33] B. Krietenstein, R. Schuhmann, P. Thoma, et al., The Per596 [18] H. Cai, W. Fu, D. Wang, et al., Three-strip microchannel plate 655 fect Boundary Approximation technique facing the challenge gated x-ray framing camera. Sensors and Actuators A: Physi- 656 of high precision field computation. Proc. of the XIX Inter598 cal. 285, 355-361 (2019). doi: 10.1016/j.sna.2018.11.028 national Linear Accelerator Conference (LINAC' 98). Chicago, 599 [19] J. L. Porter, G. P. Grim, M. Jones, et al., Hybrid CMOS detec- 658 USA, 860-862 (1998). tors for high-speed X-ray imaging. Review of Scientific Instru- 659 [34] Y. Zhuge, J. Liang, M. Fu, T. Long and H. Wang., ments. 94(6), 061101 (2023). doi: 10.1063/5.0138264 Comprehensive Overview of Power Electronics Intensive 602 [20] S. V. Hull, T. Chattopadhyay, A. D. Falcone, et al., Small pixel 661 Solutions for High-Voltage Pulse Generators.

IEEE Open hybrid CMOS x-ray detectors. Proceedings of SPIE. 10709, 662 Journal of Power Electronics. C 5, 1-20 (2024). doi: 107090E (2018). doi: 10.1117/12.2312121 10.1109/OJPEL.2023.3340220 605 [21] C. V. Griffith, A. D. Falcone, D. N. Burrows, et al., Speedster- 664 [35] Xu H, Liu B, Gou Y, et al., Research on Triode Based High EXD: a new event-driven hybrid CMOS x-ray detector. Journal 665 Re-Frequency Ultrafast Electrical Pulse Generation Technol607 of Astronomical Telescopes, Instruments, and Systems. 2(1), 666 ogy. Electronics. C 12, 1950 (2023). doi: 10.3390/electron608 016001 (2016). doi: 10.1117/1.JATIS.2.1.016001 ics12081950 609 [22] M. J. Moran, J. L. Porter, T. M. Smith, et al., A high- 668 [36] Liu J, Niu L, Peng W, et al., Application of a fast electrical speed two-frame, 1-2 ns gated X-ray CMOS imager used as 669 pulse in gated multichannel plate camera. Review of Scientific a hohlraum diagnostic on the National Ignition Facility. Re- 670 Instruments. C 78, (2007). doi: 10.1063/1.2737750 view of Scientific Instruments. 87(11), 11E203 (2016). doi:

Note: Figure translations are in progress. See original paper for figures.

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