Design and Characterization of a Coaxial Plasma Railgun for Jet Collision Experiments

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(ABSTRACT)

Plasma railguns are electromagnetic accelerators used to produce controlled high velocity plasma jets. This thesis discusses the design and characterization of a small coaxial plasma railgun intended to accelerate argon-helium plasma jets. The railgun will be used for the study of plasma shocks in jet collisions. The railgun is mounted on a KF-40 vacuum port and operated using a 90 kA, 11 kV LC pulse forming network. Existing knowledge of coaxial railgun plasma instabilities and material interactions at vacuum and plasma interfaces are applied to the design. The design of individual gun components is detailed. Jet velocity and density are characterized by analyzing diagnostic data collected from a Rogowski coil, interferometer, and photodiode. Peak line-integrated electron number densities of approximately $8 \quad 10^{15}$ cm ^{2} and jet velocities of tens of km/s are inferred from the data recorded from ten experimental pulses.

Design and Characterization of a Coaxial Plasma Railgun for Jet Collision Experiments

Mathew R. Coleman

(GENERAL AUDIENCE ABSTRACT)

Plasma is a gaseous state of matter which is electrically conductive and interacts with electric and magnetic fields. Plasmas are used in many everyday objects such as fluorescent lights, but some of the physics of plasmas are still not entirely understood. One set of plasma interactions that have not been fully explored are those which occur during high-velocity collisions between plasmas. Experiments aimed to further the understanding of these interactions require the generation of plasmas with specified properties at very high velocities.

A device known as a plasma railgun can be used to produce plasmas which meet these experimental demands. In a plasma railgun, a short pulse of current is passed through a plasma located between two parallel electrodes, or "rails". This current generates a magnetic field which propels the plasma forward. The plasma is accelerated until it leaves the muzzle of the railgun. In coaxial plasma railguns, the electrodes are concentric.

This paper discusses the design and testing of a small, relatively low power coaxial plasma railgun. Specific elements of the design are examined and the inherent physical and material difficulties of a coaxial design are explored. The experiment which was performed to confirm the properties of the plasma jets produced by the coaxial plasma railgun is explained. The results of this experiment confirm that the design succeeds in producing plasmas which meet targets for plasma properties.

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No one is an island, and no thesis is completed alone. The completion of this thesis relied upon the support of many people beyond myself.

I would first like to thank my advisors Dr. Colin Adams and Dr. Mark Pierson. My path to this point has not been the smoothest, and they have patiently been with me the whole way. Their willingness to point me in the right direction when I erred has saved me many times. Thank you also to my committee member Dr. Joseph Meadows for putting up with many false starts.

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Finally, I would like to thank my family for their support and patience.

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2.1 Early developement 3

2.2 Theory and operation 5

2.2.1 Marshall-type guns 5

2.2.2 Cheng-type guns 7

2.3 Applications 8

2.3.1 Spheromaks and other compact toroids 8

2.3.2 Z-pinches 8

2.4 Instabilities 9

2.4.1 Restrike 9

2.4.2 Blow-by 10

2.5 Material considerations 13

¨ K0 _Xj oU

3.1 Objectives 15

3.2 Experimental setup 15

3.3 Design overview 17

3.4 Material selection 19

3.5 Components 21

3.5.1 Electrodes 21

3.5.2 Insulators 24

3.5.3 Power feedthrough 26

3.5.4 Gas valve 27

3.5.5 Pulse-forming network 28

V G\9}9H§O}_¶9§_nj ©k

4.1 Diagnostic methods 29

4.1.1 Rogowski Coil 29

4.1.2 Interferometry 31

4.1.3 Photodiode 34

U |O «e§ ¨£

5.1 Delay timing optimization 36

5.2 Jet characteristics 37

5.3 Discussion 40

£ GnjHe« _nj VU

6.1 Research conclusions 45

6.2 Contributions 46

6.3 Improvements and future work 46

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ivT2 Q7 b+ H2 #H2 TT ` imb mb2/ 7Q` i?Bb Tm`TQb2 Bb i?2 TH bK
2H2+i`QK ;M2iB+ 7Q`+2b iQ ++2H2` i2 TH bK #2ir22M irQ 2H2+i
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/B772`2MiHv b? T2/ D2ib M/ T2`7Q`K /B772`2MiHv BM Qi?2` r vbX
FMQrM b +Q tB H TH bK ;mM- rBHH QT2M mT i?2 #BHBiv Q7 i?2
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bi ;M i2/ +Q tB H ;mM D2ibX

h?Bb i?2bBb /2b+`B#2b i?2 /2bB;M M/ +? ` +i2`Bx iBQM Q7 +QK
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M/ ii BM #H2 i2+?MQHQ;vX M `iB7B+B H 7mbBQM `2 +iBQM r
7BbbBQM r2 TQMb /m`B BMQM 2`2 2M?QMb Q7 J v RN8RX AM LQp2K#2`
H2bb i? M i2M v2 `b 7i2` i?2 7B`bi b2H7@bmbi BMBM; `iB7B+B
lMBp2`bBiv Q7 *?B+ ;Q- M `iB7B+B H 7mbBQM +? BM `2 +iBQM
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M22`b b r;`2 i T`QbT2+ib BM Bib mb2 7Q` +BpBHB M Tm`TQb2bX h
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Q7 i?2 ; b Q++m`b- M/ bQK2 Q7 i?2 ; b Bb BQMBx2/ BMiQ TH bK X
i?2 TH bK 7`QK QM2 2H2+i`Q/2 iQ i?2 Qi?2`- K ;M2iB+ 7B2H/ Bb
h?2 GQ`2Mix 7Q`+2 i?2M + mb2b i?2 `+ iQ ++2H2` i2 /QrM i?2 #
TH bK 2tBib i?2 ;mM- i?2 +B`+mBi Bb #`QF2M- i?2 BM/m+2/ K ;M
TH bK +QMiBMm2b KQpBM; i BiX7BM H 2tBi p2HQ+Biv(

h?`Qm;?Qmi i?2 2 `Hv RNeyb- `2b2 `+?2`b mb2/ +Q tB H TH bK
p `BQmb +QMi BMK2Mi b+?2K2bX h?2 TQbbB#BHBiB2b Q7 7mbBQ
2MiBbib ? / MQi v2i /Bb+Qp2`2/ r?B+? /2pB+2b rQmH/ #2 2772+iB

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6B;m`2 kXR, a+?2K iB+ Q7 i?2 QT2` iBQM Q7 +Q tB H;mMX h?2 /
b tB HHv bvkkX2i`B+ (

iQ BMD2+i TH bK B-MKQ;M2iBT+b (Re- `QBMR-2bM/ b?Q+Fi?X#2b (
i?2v r2`2 mbBM; +Q tB H;mMb 7Q` i?2B` 2tT2`BK2Mib- b+B2MiBb
i2` mM/2`bi M/BM; Q7 i?2 7mM/ K2Mi H T?vbB+b Q7 i?2B` QT2` i
óbHm;ô KQ/2H- r?B+? bbmK2b i? i HH BQMBx2/; b- M/QMHv BQ
;mMX h?Bb bBKTHBbiB+ TT`Q +? r b MQi i`m2 7Q` i?2 +Q tB H;m
7QHHQrBM; i?2 7B`bi rQmH/ 2D2+i KQ`2 TH bK 2p2M r?2M M2r;
#`22 ?X Air b +H2 `i? i M2r i?2Q`2iB+ H TT`Q +? r b M2+2bb
/ Ti2/ i?2 bQ@+ HH2/ óbMQrTHQrô KQ/2H 7Q` mb2 BM +Q tB H;
T`QTQb2/ 7Q` mb2 BM TBM+?2b #v JX kyLX g QBb2M2 #bHQmKi2 KQM/ BR7NB+9 (i
? p2 #22M T`QT-Q?2/;(2M2` H 7Q`K Q7 i?2 KQ/2H ? b bi v2/ i?2 b K2

6Q` M mMK;M2iBx2/ +Q tB H;mM- i?2 bMQrTHQr KQ/2H bbmK2b
+m``2Mi T`QT; i2b b M MMmH `b?22i 7`QK QM2 2H2+i`Q/2 iQ i?
mTô M2mi` H; b b Bii` p2Hb/QrM i?2 H2M;i? Q7 i?2;mMX h?mb- K
iQ i?2 p2HQ+Biv Q7 i?2 b?22iX h?2`2 Bb bbmK2/ iQ #2 MQ K;M2iB
b?22iX h?2 K;M2iB+ 7Q`+2 QM i?2 +m``2Mi b?22i + M #2 r`Bii2M
i?`Qm;? i?2 b?22i M/ i?2 BM/m+i M+2 T2` mMBi H2M;i? Q7 i?2 b?

A7 i?2 pQHi ;2 M/ + T +Bi M+2 Q7 i?2 + T +BiQ` # MF mb2/ iQ T`Q
FMQrM- i?2M bvbi2K Q7 /B772`2MiB H 2[m iBQMb + M #2 r`Bii2M
i?2 bvbi2KX JQ/B7B2/ p2`bBQMb Q7 i?2 bMQrTHQr KQ/2H HHQr
#2BM; br2Ti mT- b r2HH b bQ`2Mi HQbb(

b +Q tB H TH bK ;mMb #2+ K2 KQ`2 +QKKQM- i?2v #2; M #2BM; T
q?BH2 BMp2biB; iBM; Hi2`M iBp2 ++2H2` iBQM KQ/2b Q7 +Q tB
BM/2T2M/2MiHv `2+`2 i2/ /2Mb2 TH bK 7Q+mb bBKBH `iQ i? i +
i?2 RN8yb /m`BM; aQpB2i `2 i?2 bM/2Bb; r b p2`v bBKBH `iQ
+Q tB H ;mM- #mi ?2 QT2` i2/ Bi i Km+? ?B;?2` T`2bbm`2bX "`2 F
;mM- M/ i?2 +m``2Mi b?22i i` p2Hb /QrM i?2 #Q`2 BM bBKBH `r
.B772`2M+2b #2;BM iQ Q++m` 7i2` i?2 b?22i T bb2b i?`Qm;? i?2
TH bK b?22i +QMbi`B+ib BMiQ iB;?i- /2Mb2 +vHBM/2` i i?2 2M/
TH bK 7Q+mb2b ? p2 #22M BMp2biB; i2/ 7Q` 7mbBQM TQr2` ;2M2
T`Q/m+ i?2 QMX(

kXkXk *?2M;@ivT2 ;mMb

Sm#HB+ iBQM QM +Q tB H ;mMb bHQr2/ BM i?2 KB/@RNeyb- #mi b
BMi2`2bi2/X . ? um *?2M;- T`Q72bbQ` i i?2 lMBp2`bBiv Q7 a Mi
QM b2+QM/ 7mM+iBQM H KQ/2 Q7 +Q tB H ;mMb, i?2 /27H ;` iBQ
i?Bb KQ/2 Q7 ++2H2` iBQM iQ ;2M2` i2 ?B;? 2M2`;v- ?B;? /2MbBiv
KQ/2- /27H ;` iBQM r p2 KQp2b i?`Qm;? i?2 TH bK QTTQbBi2 i?2
i?2 T `iB+H2bX AMbi2 / Q7 T`27BHHBM; ?Bb +Q tB H ;mM- *?2M; T
i?2 #Q`2X h?Bb Tm77 r b BQMBx2/ M/ i?2M ++2H2` 7Q/ +QbX i?2
lbBM; i?Bb /2bB;M- *?2M; +?B2p2/ 2tBi p2HQ+BiB2b r?B+? r2`2 Q`
;mMb QT2` iBM; BM i?2 bMQ`T+Qr2K ?B/; p2HQ+BiB2b ; p2 +Q tB H
b K2i?Q/ Q7 bT +2 T`QTmHbBQM- r?B+? r b i?2 T`BK `v 7Q+mb

i?`Qm;?Qmi i?2)RNdyb(

kXj TTHB+ iBQMb

kXjXR aT?2`QK Fb M/ Qi?2` +QKT +i iQ`QB/b

_2b2 `+? BMiQ K ;M2iBx2/ ;mMb TB+F2/ mT BM i?2 RN3ybX J ;M2iB
#2 mb2/ iQ ;2M2` i2 bi #H2 +QKT +i TH bK iQ`QB/b 7Q` Mm+H2 `
irQ ivT2b Q7 +QKT +i iQ`QB/ TH bK b, 7B2H/@`2p2`b2/ +QM7B;m
aT?2`QK F iQ`QB/b ? p2 iQ`QB/ H K ;M2iB+ 7B2H/- r?BH2 6_* iQ
? p2 #22M Q7 T`BK `v BMi2`2bi rBi? `2; `/ iQ +Q tB H ;mMbX hQ ;2
+Q tB H ;mM- bQH2MQB/ H 2H2+i`QK ;M2i Bb ivTB+ HHv TH +2/
Bb ?QHHQr BM i?Bb H vQmiX h?2 K ;M2iB+ 7B2H/ HBM2b r?B+? T
7`QK i?Bb 2H2+i`QK ;M2i `2 TT`QtBK i2Hv T2`T2M/B+mH `iQ i?
i?2 TH bK rBi?BM i?2 ;mMX b i?2 TH bK T bb2b i?`Qm;? i?2 7B2H
HQM; rBi? BiX i i?2 KmxxH2 Q7 i?2 ;mM- i?2 7B2H/ /27Q`Kb M/ i?
iQ`mb@b? T2/ K ;M2iB+ 7B2H/ iQ i?2 TH bK - r?B+? +QMi BMb B
bi #BHBiv M/ +QM7BM2K2Mi 7Q` bB;MB7B+ Mi H2M;i?b Q7 iBK2-
BMD2+iBQM K2i?Q/b 7Q` 7mkim`2X7mbBQM `2 +iQ`b(

kXjXk w@TBM+?2b

AM i?2 kRbi +2Mim`v- +Q tB H TH bK ;mMb ? p2 #22M mb2/ iQ ;2
TBM+?2bX lbBM; +Q tB H ;mM- TH bK Bb ++2H2` i2/ BM ó[m bB
`2;BQMX h?Bb [m bB@bi2 /v@bi i2 Bb +?B2p2/ #v TTHvBM; p2`
; bX b HQM; b i?2 +m``2Mi TmHb2 /2+ v Bb HQM;2`i? M i?2 iBK2 B
KmxxH2 Q7 i?2 ;mM- [m bB@bi2 /vjy)HXQrb+i?M2 #2 2 2bib#2b p2 b ?2B(Mbi #

bbQ+B i2/ rBi? w@TBM+?2b- /B772`2Mi TT`Q +?2b ? p2 #22M i F
HX ? p2 mb2/ b?2 `2/ 7HQr rBi?BM i?2 x@TBM+?2b- /B772`2Mi TT`Q +?2b ? p2 #22M i F
#22M b?QrM iQ #2 2772+iBp2 2tT2`BK2Mi TT`Q +?2b ? p2 #22M i F
T`Q/m+2/ M2mi`X QMb7 72`2Mi TT`Q +? BKTHQ/2b i?BM b?2HH Q7
QMiQ i?2 TBM+? iQ bmTT`2bb i?2 BMbi #BHBiB2bX AM i?2b2 /2bB
;2M2` i2 i?2 x

BM +Q tB H TH bK ;mMb `2/m+2 i?2 BM+B/2M+2 Q7 b2+QM/ `v `+
iQ `2/m+BM; `2bi`BF2 `2 iQ /2+`2 b2 /`BpBM; +m``2Mi M/ pQHi
/2+`2 b2b i?2 #H iBQM` i2 Q7 BMbmH iQ`b M/ 2H2+i`Q/2bX GQr
#2 +?Qb2M 7Q` i?2 ;mMb `2/m+2 i?2 BM+B/2M+2 Q7 b2+QM(

kX9Xk "HQr@#v

_ /B H /B772`2M+2b BM TH bK 2tBi p2HQ+Biv 7`QK +Q tB H ;mM
RNe9yB(M/ i?2B` B/2MiB7B+ iBQM rBi? TH bK BMbi #BH9 iB2b r b
#mi i`m2 mM/2`bi M/BM; Q7 i?2 +QMb2[m2M+2b rQmH/ MQi Q++r
T`2bbm`2 BM +Q tB H ;mM p `B2b rBi? i?2 BMp2`b2 b[m `2 Q7 ` /Br
Bb ?B;?2` +HQb2` iQ i?2 +2Mi2` 2H2+i`Q/2- M/ TH bK T `iB+H2b
b i?2 BMbB/2 Q7 i?2 +m``2Mi b?22i #2;BMb iQ T bb i?2 QmibB/2- I
M/ +QKT`2bb i?2 `2bi Q7 i?2 b?22i ; BMbi i?2 Qmi2` 2H2+i`Q/2X
T `i Q7 i?2 TH bK K bb ++2H2` iBM; iQ M 2ti`2K2Hv ?B;? p2HQ+I
i?2 TH bK - r?B+? Bb +QKT`2bb2/ ; BMbi i?2 Qmi2` r HH M/ 2tBib
kXk BHHmbi` i2b i?Bb T`Q+2bbX AM K Mv + b2b- Bi Bb /2bB` #H2 7
bBKBH ` p2HQ+BiB2b- M/ 7Q` i?Bb iQ ? TT2M #HQr@#v Kmbi #2
M2 ` i?2 BMM2` 2H2+i`Q/2b b2T ` i2b 7`QK i?2 r HH- +m``2Mi Kmb
i?`Qm;? i?2 `2K BMBM; ii +?2/ TH bK X AM //BiBQM- i?Bb `2K BM
bFBM /` ; b Bi ++2H2` i2bX h?2b2 irQ +QK#BM2/ 7 +iQ`b + mb2
BMM2` 2H2+i`Q/2X h?2 Qmi2` 2H2+i`Q/2 HbQ bmbi BMb BM+`2 b
TH bK Bb ?2 i2/ /m2 iQ +QKT`2bbBQM r?BH2 Bi bHQrHv i` p2Hb /
bT2Mi BMbB/2 i?2 ;mM + mb2 BM+`2 b2/ +QM/m+iBQM M/ ` /B iBQ
i?mb BM+`2 b2/ K2HiBM; M/ #H iBQMX "HQr@#v Q++m`b BM #Qi?
;mMb( )( )( )X

b #HQr@#v Bb +QMb2[m2M+2 Q7 i?2 K ;M2iB+ T`2bbm`2 BMbB/

6B;m`2 kXk, AHHmbi` iBQM Q7 i?2 2pQHmiBQM Q7 #HQr@#v BMbB
`2T`2b2Mi i?2 2H2+i`Q/2b- ;` v `2;BQMb i?2 #`22+? BMbmH iQ`b-
mMb? /2/ `2;BQMb 2KTiv bT +2X "HQr@#v /2p2HQTb `B;?ir `/b BM

2MiB`2Hv Bb p2`v /B77B+mHiX hQ 7mHHv pQB/ i?2 QMb2i Q7 #HQr
Q7 i?2 TH bK ;mM b?QmH/ #2 b b?Q`i b TQbbB#H2X 6Q`+Q tB H
i? M 8yy F -i?2 ++2H2` iBQM T2`BQ/ b?QmH/ #2 HBKBi2/ iQ H2bb i
Bb MQi +?B2p #H2- /B772`2Mi TT`Q +?2b + M #2 i F2M iQ BM+`2
2ti2M/ i?2 TQi2MiB H ++2H2` iBQM T2`BQ/X h?2 QMb2i iBK2 + M
D2+iBQM /2MbBiv- +m``2Mi TmHb2 b? T2b- TH bK i2KT2` im`2- M
J `b? HH@ivT2 +Q tB H ;mMb bm772` i?2 KQbi 7`QK #HQr@#vX "
/2+`2 b2b` /B HHv- K bb b?QmH/ #2 +QM+2Mi` i2/ M2 `i?2 +2Mi`
1/r² BMBiB H ` /B H /2MbBiv /Bbi`B#miBQM- #HQr@#v + M #2 iQi H
M/ T`2bbm`2 /Bbi`B#miBQMb rBHH + M+2H QmiX h?Bb /2MbBiv /Bb
i?2 Tm772/@; b K2i?Q/ Q7 k*e?-2#Mm i@BivB2 2miM2 K2Hv /B77B+mHi iQ `
/Bbi`B#miBQM mbBM; bi M/ `/ +Q tB H ;mM ;2QK2i`vX hBK2 iQ #H
#v HQr2`BM; /`BpBM; +m``2MiX G2bb #HQr@#v Q++m`b BM +Q tB
2p2M B7 i?2B` 2H2+i`Q/2b `2 2ti2M/2/ iQ HHQr i?2K iQ `2 +? i?2
+m``2Mi ;mMbX lM7Q`imM i2Hv- HQM;2` ;mMb ? p2 T`Q#H2Kb rBi

M BM?2`2Mi i` /2@Q77 rBi? i?Bb TT`Q +?X AM+`2 b2b BM TH b
mMiBH #HQr@#v Q++m`bX b /2pB+2b `2 Q7i2M /2bB;M2/ iQ +?B2
?Qr2p2`- i?Bb HBKBi iBQM K v bBKTHv M22/ iQ #2 /2bB;M2/ `Qm
HBKBi2/ +QMi`QH Qp2` i?2 i2KT2` im`2 Q7 TH bK b +`2 i2/ /m`BM
T2` im`2 + M QMHv #2 +QMi`QHH2/ 2772+iBp2Hv B7 T`2@;2M2` i2
h?2 F2v bT2+i Q7 2H2+i`Q/2 ;2QK2i`v r?B+? BKT +ib #HQr@#v Bb
h?Bb Q++m`b 7Q`irQ `2 bQMbX hQi H K ;M2iB+ T`2bbm`2 Bb /2T2M
H2M;i? Q7 i?2 2H2+i`Q/2b- i?2 bQ@+ HH2/ BM/m+i M+2 ;` /B2MiX
i?2 BM/m+i M+2 Q7 ;Bp2M TQBMi BM i?2 bT +2 #2ir22M i?2 2H2+
h?mb- i?2 ` iBQ Q7 i?2 ` /BB Q7 i?2 Qmi2` M/ BMM2` 2H2+i`Q/2b B
i M+2 ;` /B2MiX "HQr@#v iBK2 /2+`2 b2b rBi? M BM+`2 b2 BM i?2
#v M BM+`2 b2 BM i?2 ` iBQ #2ir22M i?2 Qmi2` M/ BMM2` 2H2+i`
M mTT2` HBKBi Q7 k,R 2H2+i`Q/2 ` /Bmb ` iBQ iQ `2/m+2 i?2 277
iQi H ` /Bmb Q7 #Qi? i?2 BMM2` M/ Qmi2` 2H2+i`Q/2b ? b i?2 2772
h?mb- H `;2` 2H2+i`Q/2b `2 /2bB` #H2 7`QK #HQr@#v T2`bT2+i
#2 7QmM/ rBi? qBi?2`bTQQM 2i HX- r?Q mb2 M Hi2`M iBp2 ó?Q
`2/m+BM; i?2 2772+ib Q7 #HQr@#vX SH bK Bb 2H2+i`Qi?2`K HHv
b KQ/2H2/ #v * bbB#`vX Ai i?2M i` p2Hb BMiQ +QM+ p2 `2;BQM-
+QKT`2bb2/ ; BMbi i?2 BMM2` 2H2+i`Q/2X h?Bb HHQrb i?2 /2MbB
B/2 H + b2X h?2 TH bK i?2M 2tT M/b i?`Qm;? +QMp2t `2;BQM iQ
bHB;?iHv ++2H2` iBM; i?2 7HQrX h?Bb ;2QK2i`v pQB/b #HQr@#v
2tT2MbBp2 7Q` KQbi TTHB+ iBQMb- M/ MQi M2+2bb `v7)Q` /2pB+
(9 8 9 9) X

kX8 J i2`B H +QMbB/2` iBQMb

PM2 Q7 i?2 T`BK `v ii` +iBQMb Q7 +Q tB H TH bK ;mMb b +QKT `
Bb i?2 `2H iBp2Hv ?B;? Tm`Biv Q7 i?2B` 2D2+i2/ TH bK BM +QKT
T`QT2`iv ? b #22M MQiB+2/ bBM+2 2 `Hv BM i?2B` /2p2HQTK2Mi-
i?2 mb27mHM2bb Q7 +Q h?2 2 ;`2M?(22 K BM bQm`+2b Q7 BKTm`BiB
TH bK bX h?2 7B`bi Bb BKTm`BiB2b H`2 /v T`2b2Mi BM i?2 ; b 72
i F2M iQ +[mB`2 ?B;?@Tm`Biv ; b bmTTHB2b- #mi i?2b2 BKTm`BiB
i?2 iQi HX h?2 b2+QM/ bQm`+2 Q7 BKTm`BiB2b Bb 7`QK i?2 TH bK
2H2+i`Q/2bX AM HBM2 `TH bK ` BH;mMb- 2`QbBQM Q7 i?2 BMbm
bQm`+2 Q7 BKTm`BiB2b i?2 bK HH2`TH bK @7 +BM;bm`7 +2 `2 Q
TH bK ;mMb- i?Bb Bb H2bb Q7 +QM+2`MX _2; `/H2bb- HQr@2`Q
+QMi2Mi BM TH bK 2D2+i2/ 7`QK +Q tB H ;mMbX HQM;rBi? Qmi
?B;?@p +mmK bvbi2Kb- HBKBi2/ p `B2iv Q7 BMbmH iQ`b `2 bmB
T2`7Q`KBM;BMbmH iQ`b ? p2 ?B;? i?2`K H +QM/m+iBpBiv HQM;r
* M/B/ i2b 7Q`i?2b2 K i2`B Hb BM+Hm/2 K2i H QtB/2b bm+? b Hm
bQK2 KB+ @# b2/;H bb +2` KB+b bm+? b J +Q`- M/ bQK2 Qi?2` /p
HmKBM M/ K2i H QtB/2b T`Q/m+2 i?2 H2 bQ/X QmMi Q7 BKTm`Bi

h?2 T`BK `v bQm`+2 Q7 BKTm`BiB2b BM +Q tB H ;mMb Bb #H i2/ K
Q7 i?2 BMM2` M/ Qmi2` 2H2+i`Q/2b Q7 i?2 TH2bK H;mMb M/ 2`QbB
/m2 iQ p `B2iv Q7 + mb2b- #mi i?2 KQbi bB;MB7B+ Mi Bb K2HiBM
:2QK2i`B+ H +? M;2b r?B+? `2/m+2 +m``2Mi /2MbBiB2bX HbQ /2+`
+Q tB H ;mM 2H2+i`Q/2b `2 ivTB+ HHv +QMbi`m+i2/ 7`QK K2i Hb-
KQ`2 K bbBp2 i? M BQMb 2`Q/2/ 7`QK BMbmH iQ` K i2`B H Q` 7`Q
1p2M bK HH KQmMib Q7 2`Q/2/ 2H2+i`Q/2 K i2`B H ? p2 H `;2 BM
/m2 iQ i?2B` K bb M/ i?2B` HBF2HB?QQ/ iQ + mb2 `2bi`BF2X h?2
K i2`B H Bb bi BMH2bb bi22H- ?Qr2p2` Bi 2tT2`B2M+2b `2H iBp2H

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bi BMH2bb bi22H ? b M2; iBp2 2772+i QM BMBiB H M9bX2+QM/ `
P7 bi M/ `/ K i2`B Hb- +QTT2` HHQv 2H2+i`Q/2b mM/2`;Q i?2 H2
`+bX Sm`2 +QTT2`+ M #2 bQK2r? i /B77B+mHi iQ K +?BM2- #mi i
HHQv bB;MB7B+ MiHv BKT`Qp2b K +?BM #BHBiv M/ K v `2/m+2
+QTT2` HHQvb KQ`2 mb27mH 2H2+i`Q/2 K i2`B HbX Pi?2` //BiBp
#H iBQM i? M 8ym(Q),bi2M(

*? Ti2`j

.2bB;M

jXR P#D2+iBp2b

h?2 +Q tB H TH bK ` BH;mM r b /2bB;M2/ iQ ++2H2` i2 TH bK D
/2MbBiB2b QM10 ?2 (Q3) /2 `T iQ p2HQ+BiB2b Q7 iH2 biRy FKfb- T`272
ky FKfbX h?2b2 T`QT2`iB2b `2 +QMbB/2`2/ bm77B+B2Mi iQ T2`7
2tT2`BK2MibX a2+QM/ `v T`BQ`BiB2b BM+Hm/2/ bBx2- +Qbi- 2 b2
rBi? Qi?2` H # 2[mBTK2MiX h?2 +Q tB H ;mM r b /2bB;M2/ iQ #2
M/ 7mim`2 E6@9y p +mmK TQ`ib p BH #H2 i i?2 oB`;BMB h2+? *
1M;BM22`BM; _2b2 `+?X h?2 +Qbi Q7 K i2`B Hb M/ 7 #`B+ iBQM
i?Qmb M/ /QHH `bX h?2 /2bB;M r b BMi2M/2/ iQ #2 2 bBHv K BMi
B7 M2+2bb `vX 6BM HHv- BMi2;` iBQM rBi? 2tBbiBM; H # 2[mBTK
;mM iQ 7mM+iBQMX h?2 /2bB;M /2+BbBQMb /Bb+mbb2/ BM i?2 7QH
i?2b2 +Q`2 Q#D2+iBp2bX

jXk 1tT2`BK2Mi H b2imT

*QMbi`m+iBQM M/ QT2` iBQM Q7 i?2 +Q tB H TH bK ;mM iQQF T
T`BQ` rQ`F mbBM; i?2 oB`;BMB h2+? 8 kX BM?2 `+ QHtB K H ;mBMH KmQM (Mib
bi M/ `/ E6@9y 7H M;2 QM RXk K HQM ³ -pR+ k mBK K+2 i2K # 2y`X d h?2
p +mmK +? K#2` ? b irQ E6@9y TQ`ib M/ 2B;?i jy +K TQ`ib r?B+? -

6B;m`2 jXR, R,kj b+ H2 iQT@/QrM pB2r Q7 i?2 i2biBM; 2M

9y / Ti2`bX 6Q` BMBiB H +? ` +i2`Bx iBQM i2biBM;- i?2 ;mM r b
+? K#2`- T2`T2M/B+mH ` iQ irQ jy +K pB2rTQ`ibX .B ;MQbiB+b r2
i #H2 QM QM2 bB/2 Q7 i?2 +? K#2`- M/ MQTiB+ H #`2 /#Q `/QM i
jXR aT2+B7B+ /B ;MQbiB+b rBHH 8X2 h?B2 +mbK#2 `M2 *?? 2b TT`QtBK
Ry iQ`` /m`BM; MQ`K H i2biBM;X h?Bb T`2bbm`2 Bb `2 +?2/ #v 7B
`Qm5M/10 2 iQ`` mbBM; h`Bp + .9y" QBH b2 H2/ `Qi `v p M2 /m H bi
hQ``K bi2` hJ8yy ky BM+? BMH2i +`vQTmKT Bb i?2M mb2/ iQ `2 +?

a 72iv K2 bm`2b KB``Q` i?Qb2 mb2/ 7Q` QT2` iBQM) 8MX Q7 h?2 b2HBM2
BM+Hm/2 ? `/r `2 M/ bQ7ir `2 BMi2`HQ+Fb r?B+? Kmbi #2 +iBp i2/
FBHH brBi+? r?B+? /Bb+QMM2+ib HH TQr2` bmTTHv- M/ `22/ brB
/QQ` r?B+? /Q2b i?2 b K2X

6B;m`2 jXk, _2M/2`BM; Q7 i?2 2ti2`BQ` Q7 i?2 +Q tB H

jXj .2bB;M Qp2`pB2r

*Q tB H TH bK ;mMb `2 KQ`2 /B77B+mHi iQ +QMbi`m+i i? M HBM2
h?2 +Q tB H +QM7B;m` iBQM Q7 i?2 2H2+i`Q/2b BMi`Q/m+2b KQ`2
b2 HBM; TQBMib- M/ ii +?K2Mi K2i?Q/bX *vHBM/`B+ H +QKTQM
7 #`B+ iBQM b r2HHX J Mv T `ib Q7 i?2 +Q tB H ;mM Kmbi #2 TmH
`2KQp2/- r?B+? `mH2b Qmi i?2 mb2 Q7 T2`K M2Mi /?2bBp2 2t+27

h?2 7BM H /2bB;M +QMbBbib Q7 BMM2` M/ Qmi2` 2H2+i`Q/2b- BM
i?`22 BMbmH iQ`b- M/ p `B2iv Q7 7BiiBM;b M/ ? `/r `2X h?2 B
`2 b2T ` i2/ #v TH bK @7 +BM; BMbmH iQ` M/ M BMi2`M H BM
`2 ii +?2/ iQ 2 +? Qi?2` rBi? M /?2bBp2- M/ ?2H/ BM TH +2 rBi
h?2 Qmi2` 2H2+i`Q/2 Bb i?`2 /2/ QMiQ TBT2 MBTTH2- i?2 Qi?2` 2
+mbiQK@/2bB;M2/ E6@9y #H MFX h?2 BMM2` 2H2+i`Q/2 2ti2M/b i?
Bb 72/ BMiQ i?2 bb2K#Hv i?`Qm;? i?`2 /2/ +QMM2+iBQM i i?2 2
K +?BM2/ +QHH `Bb ii +?2/ iQ i?2 BMM2` 2H2+i`Q/2 iQ +i b M BM
+QM+2Mi`B+ TBT2 `2/m+2` T`2bb 7Bi iQ i?2 +mbiQK #H MF +ib b
M 2ti2`M H BMbmH iQ` bBib #2ir22M i?2 Qmi2` TQr2` 722/i?`Qm;

6B;m`2 jXj, *mi r v pB2r Q7 i?2 +Q tB H ;mM b?QrBM; RV i?2 BM
2H2+i`Q/2- jV TH bK @7 +BM; BMbmH iQ`- 9V BMi2`M H BMbmH
TQr2` 722/i?`Qm;?- dV +Q tB H + #H2 Qmi2` +QMM2+iQ`b- 3V +Q
722/i?`Qm;? +QHH `- NV ; b Tm77@p Hp2 bi M/Q77- RyV ; b Tm77

T`2p2Mi `+BM;i?`Qm;? B`X `2M/2`BM;Q7 i?2 2ti2`M H pB2r Q7 i

6B;mjX2kM/ +mi r v pB2r BjXj6B;mB`2i Q7 ;mM +QKTQM2Mib + M #2 b

jXXR h?2 ;mM + M #2 bb2K#H2/ M//Bb bb2K#H2/ 7Q` `2HQ+ iBQM

Q7 / K ;2/ T `ib BM K ii2` Q7 KBMmi2bX

h?2`2 `2irQ T`BK `v b2 HBM;bm`7 +2b QM i?2 +Q tB H ;mMX h?2 7

#v 7HmQ`Q2H biQK2` Q@`BM; +QKT`2bb2/ #2ir22M b?QmH/2` C

mTT2` bm`7 +2 Q7 i?2 BMi2`M H BMbmH iQ`X a2 HBM; 7Q`+2 Bb

b+`2r2/ BMiQ i?2 +mbiQK E6@9y #H MFX Air b BMBiB HHv #2HB2

7Q`+2 rQmH/ #2 M2+2bb `v iQ K BMi BM i?Bb b2 H- #mi Bi ? b #22M

p +mmK rBi? H2bb i? M ? H7 i?2 2tT2+i2/ 7Q`+2X b2`BQmb/` r# +

HBM2 `` BH;mM Bb i?2 2ti2MbBp2 mb2 Q7 GQ+iBi2 N9Nk- HbQ F

i` /2 M K2 hQ`` a2 HX h?Bb ?2 pv mb2 Q7 hQ`` a2 H K F2b bb2K#I

HBM2 `;mM /B77B+mHi M/iBK2@+QMbmKBM;X AM //BiBQM iQ p

Q7 hQ`` a2 H QM i?2 +Q tB H ;mM Bb M2+2bb `v #2+ mb2 Q7 i?2 KQ

b2 H Bb HQ+ i2/ #2ir22M i?2 Qmi2` bm`7 +2 Q7 i?2 BMi2`M H BMbm

6B;m`2 jX9, *mi r v pB2r Q7 i?2 +Q tB H ;mM 7Q+mbBM; QM i?2

b2 H Bb i?2 b2+QM/ TQBMi QM i?2 ;mM r?2`2 M /?2bBp2 Bb mb2/X
Q@`BM; +QKT`2bb2/ #2ir22M i?2 Qmi2` 2H2+i`Q/2 M/ i?2 QTTQbB
#mi i?Bb r b MQi 2 bBHv 7 #`B+ i2/X hQ`` a2 H TTHB2/ `QmM/ i
7Q`Kb i?2 b2 H BMbi2 /X +mi r v pB2r 7Q+mbBM; QMjX9 i`BTH2

jX9 J i2`B H b2H2+iBQM

h?2 T`BK `v +QMbi` BMib QM K i2`B H b2H2+iBQM BM i?2 +Q tB H
2`iB2b M/ #m/;2iX h?2b2 i` Bib r2`2 Q7i2M BM QTTQbBiBQM iQ
i?2 p BH #H2 QTiBQMb 7Q` K i2`B Hb BM i?2 ;mMX a2p2` H /Qx2M
BM2/ #27Q`2 i?2 7BM H + M/B/ i2b r2`2 +?Qb2M M/ i?2 +QKTQM2
+QKT`QKBb2b ? / iQ #2 K /2 BM K i2`B H +?QB+2 7Q` i?2 7BM H /2

*QKTQM2Mib mb2/ BM HH p +mmK bvbi2Kb 7 +2 irQ T`BK `v K i2`B
i?2 +Q tB H ;mM iQ #2 bm++2bb7mH- Mv K i2`B Hb mb2/ BM Bib /
+`Bi2`B , 7B`bi- i?2v Kmbi #2 p +mmK +QKT iB#H2 @ i?2v Kmbi ? p2

M/ /B77mbBQM- M/ Kmbi K BMi BM i?2B` b? T2 mM/2` ?B;? Q` m
i?2 K i2`B Hb +?Qb2M Kmbi #2 K2+? MB+ HHv `Q#mbi bQ i? i i?2
QT2` iBQM- M/ /Bb bb2K#HvX hrQ //BiBQM H `2[mB`2K2Mib r2`2
SQr2` 722/i?`Qm;?b M/ 2H2+i`Q/2b Kmbi #2 + T #H2 Q7 + ``vBM;?
7 +BM; K i2`B Hb Kmbi #2 `2bBbi Mi iQ i?2 2ti`2K2 ?2 i 7Hmt bbQ+

Pmi; bbBM; Q7 K i2`B Hb Q++m`b r?2M i?2 T`2bbm`2 Q7 i?2 p +m
HQr2` i? M i?2 p TQ` T`2bbm`2 Q7 2Bi?2` i?2 K i2`B H Bib2H7- BKT
#bQ`#2/ BMiQ i?2 K i2`B HX J2i Hb /Q MQi i2M/ iQ #bQ`# Km+? ;
bQK2iBK2b + MX S`Q#H2K iB+ K2i Hb i?mb i2M/ iQ ? p2 ?B;? p TQ
MQM@K2i HHB+ HHQv Mib K v HbQ Qmi; b bB;MB7B+ MiHvX HH
H2 /- K ;M2bBmK- bmHT?m`- Q` xBM+ b?QmH/ #2 pQB/2/ 7Q` i?
T`Q#H2K iB+ #2+ mb2 i?2v #Qi? ? p2 ?B;?2` p TQ` T`2bbm`2b- M
TH biB+b HbQ ? p2 ?B;? TQ`QbBivX 62r TH biB+b `2 bmBi #H2
TTHB+ iBQMbX LQM@TQ`Qmb +2` KB+b `2 ;MX2`hH2v mbM7B7Q`
QT2` i2/ mbBM; BMD2+i2/ `;QM ; b- M/ /B77mbBQM Q7 BMD2+i2
iQ `;QMöb `2H iBp2Hv ?B;? KQH2+mH `r2B;?iX

aBM+2 i?2 +Q tB H ;mM Bb QT2` i2/ i `QQK i2KT2` im`2- rBi? ?B
T2`B2M+2/ QM i?2 TH bK @7 +BM; bm`7 +2b- K2+? MB+ H T`QT2
M Bbbm2X aQK2 K i2`B Hb `2 `mH2/ Qmi- bm+? b ;` T?Bi2 7Q` 2
r2 F +2` KB+b M/ TH biB+b 7Q` BMbmH iQ`bX b i?2b2 K i2`B Hb i
i?2 MmK#2` Q7 ++2Ti #H2 K i2`B Hb Bb MQi bB;MB7B+ MiHv `2/m
F TiQMX J2+? MB+ H bi`2M;i? Bb M2+2bb `v- #mi MQi /B77B+mHi

lM7Q`imM i2Hv- +QKTQM2Mib K /2 Q7 K i2`B Hb r?B+? #2bi 7mH
iQ #2 p2`v 2tT2MbBp2X h?2v `2 2Bi?2` K /2 Q7 2tT2MbBp2 K i2`
iBK2@+QMbmKBM; 7 #`B+ iBQM T`Q+2bb2b- Q` #Qi?X J i2`B Hb
K2+? MB+ HHv `Q#mbi `2 HBKBi2/ iQ +2` KB+b- +2`i BM K2i H HH

Q7 TH biB+bX J2i Hb rBi? HQr K2HiBM; TQBMi Q` i?2`K H +QM/m+
7 +BM; TTHB+ iBQMb- b `2 HH TH biB+bX J Mv Qi?2`rBb2 pB
i?2`K H bi`2bb Q7 TH bK 2tTQbm`2X *m``2Mi@+ ``vBM; M/ TH b
HQM; rBi? +Qbi +QMbB/2` iBQMb Q7 BM/BpB/m H +QKTQM2Mib r
b2+iBQMX

jX8 *QKTQM2Mib

jX8XR 1H2+i`Q/2b

h?2 2H2+i`Q/2b `2 i?2 KQbi BKTQ`i Mi +QKTQM2Mib Q7 Mv ` BH;
i?2 BMM2` 2H2+i`Q/2 Bb +vHBM/`B+ H `Q/ rBi? /B K2i2` Q7 RX
+KX AMD2+i2/ ; b 2Mi2`b i?2 #`22+? Q7 i?2 ;mM i?`Qm;? irQ bK HH
i?2 KmxxH2 2M/ Q7 i?2 ;mMX h?Bb H2M;i? +Q``2bTQM/b rBi? i?2
`2K BMBM; R8Xy +K +QMM2+ib iQ i?2 BMM2` TQr2` 722/i?`Qm;? M
7Q` i?2 ;mMX h?2 Qmi2` 2H2+i`Q/2 Bb kkX8 +K BM H2M;i? rBi? M B
M Qmi2` /B K2i2` Q7 jXyy +KX "HQr@#v M/ `2bi`BF2 `2 K DQ` bQ
+Q tB H TH bK ;mMbX AM i?Bb + b2- #HQr@#v Bb mMHBF2Hv- b B
7Q` ` BH;mM- Ny F X h?2 ;mM ;2QK2i`v r b HbQ /2bB;M2/ iQ KBM
.B772`2M+2b #2ir22M ++2H2` iBQM QM i?2 bm`7 +2b Q7 i?2 BMM
rBi? 2H2+i`Q/2 ` /BB ` iBQ- M/ #HQr@#v /2p2HQTb KQ`2 [mB+FH
H9(8 `2+QKK2M/ i? i ++2H2` iBQM /B772`2M+2b ;`2 i2` i? M QM2
#2 pQB/2/X h?Bb +Q``2bTQM/b rBi? M 2H2+i`Q/2 ` /BB ` iBQ Q7 I
` /BB 7Q` i?2 +Q tB H TH bK ` BH;mM Bb RX3R,RX _2bi`BF2 Bb +
_2bi`BF2 ` `2Hv + mb2b T`Q#H2Kb 7Q` ` BH;mMb QT2` i2/ i mM/2
K2i2`b BM H2M;i?X h?2 +Q tB H TH bK ` BH;mM Bb b?Q`i 2MQm;?
H27i i?2 ;mM #27Q`2 bB;MB7B+ Mi KQmMi Q7 +m``2Mi + M #2 HQ

kk +Ñžÿ ¶ kY /¶ ÔÌé

h #H2 jXR, *QKTQM2Mib mb2/ BM i?2 /2bB;M Q7 i?2 +Q tB H ;mM
i?2B` 7 #`B+ iBQMX

* i2;Q`v	*QKTQM2Mi	J i2`B H
1H2+i`Q/2	AMM2` Pmi2`	50W imM;bi2M@+QTT2` 50W imM;bi2M@+QTT2`
AMbmH iQ`SH bK @7	+BM; J +Q` AMi2`M H 1ti2`M H	S11E So*
SQr2` 722/i?`Qm;	AMM2` Pmi2` Pmi2` +QMM2+iQ	jey #` bb jy9 bi BMH2bb bi22H jey #` bb
: b 722/i?`Qm;	ai?M/Q77 +QMM2+iQ Sm77@p Hp2	H USPJV jy9 Ti2i` BMH2bb bi22H

i H jH)(X

b i?2v `2 TH bK @7 +BM; M/ +m``2Mi@+ ``vBM;- K i2`B Hb mb2/
2p2`v +`Bi2`B 7Q` K i2`B H b2H2+iBQMX AM //BiBQM- i?2 +Q tB
K i2`B H Kmbi #2 K +?BM #H2 mbBM; H i?2 -X i?2 b BB2 +Hmb i2/ BM H b?7
#Qi? +m``2Mi + T +Biv M/ 2H2+i`Q/2 2`QbBQM `2 jXR ;?Q@iTBmMBiv +
M 2t KTH2 Q7 2`QbBQM ` i2b 7Q` /B772`2Mi +QTT2` HHQvbX Sm`
bB;MB7B+ Mi +QM+2`M QM im`M2/ TB2+2 #2+ mb2 Mv BMi2`M H
iQ `2KQp2X h?Bb bm;;2bib i? i KQ`2 K +?BM #H2 +QTT2` HHQv b
/Q2b MQi K22i p +mmK +QKT iB#BHBiv `2[mB`2K2Mib M/ HmKBM
TH bK #H iBQM- b /Q KQbi HmKBMmK HHQvbX 8yW imM;bi2M-
QM 7Q` i?2 7BM H 2H2+i`Q/2 /2bB;MbX hmM;bi2M@+QTT2` ? b `2
bBKBH ` #H iBQM ` i2b iQ Tm`2 +QTT2`X hmM;bi2M@+QTT2` Bb K
#mi i?2 /2+`2 b2/ K +?BMBM; iBK2 H2 /b iQ +Qbi b pBM;bX h?2 +
b?QrM BM 6XX m`2 jXX