Sandia National Laboratories Mission Research Corporation NRL Cornell

Single-Gap Accelerator: Status and Working Group Plans

Craig Olson[1], Paul Ottinger[2], Jess Neri[2], Tim Renk[1], Stan Humphries[3], Dave Rose[4], Bruce Weber[2], Frank Young[2], John Greenly[5], Dale Welch,[4] John Maenchen[1], Steve Slutz[1], Mike Desjarlais[1], Mike Cuneo[1]

[1]Sandia National Laboratories, Albuquerque, NM
[2]Naval Research Laboratories, Washington, DC
[3]UNM, Albuquerque, NM (retired)
[4]ATK Mission Research, Albuquerque, NM
[5]Cornell University, Ithica, NY

Workshop on Accelerator Driven HEDP
Lawrence Berkeley National Laboratory
Berkeley, CA
October 26-29, 2004

Outline

Pre-Workshop held at SNL on October 19, 2004

HEDP examples with Pulsed Power facilities

Questions regarding charge to group

Beam parameters wanted for HEDP

General comments on single-stage diodes

Possible facilities for single-stage diodes

Single-stage diode options (three)

Ionization Front Accelerator (IFA) option

Summary

Pre-Workshop on Single-Stage Ion Diodes for HEDP for HIF-VNL

Sandia National Laboratories
Area IV, Building 962, Room 1402
Tuesday, October 19, 2004

9:00 - 9:10 Assemble Group: SNL- Craig Olson, Tim Renk,
NRL- Paul Ottinger, Jess Neri,
Bruce Weber, Frank Young (as available

9:10 - 12:00 Review HEDP requirements as per the HIF-VNL documents

Assess the utility of each of the following to reach the HEDP goals:

(1) Mercury facility at NRL
(2) RITS facility at SNL
(3) RHEPP/MAP facility at SNL
(4) High Impedance Ion Diode with no requirement on efficiency
(5) Ionization Front Accelerator
(6) Other options? (Cornell, etc.)

12:00-1:00 Lunch at BEA's with *special guest* Stan Humphries

1:00- 4:00 Consult with various experts:

Dave Rose (MRC)
John Greenly (Cornell)
Steve Slutz
Mike Desjarlais
(John Maenchen)
(Dave Hanson)
LBNL if we need answers to charge
(Ed Lee, Simon Yu, John Barnard, Grant Logan, etc,)

4:00 - 5:00 Summarize our position for the list of 6 possibilities

HEDP examples with Pulsed Power facilities

electron beam - rod pinch on Gamble II	25 eV
ion beam (D): PRD on Gamble II	15 eV
ion beam (p): (diode on Sabre)	30 eV
ion beam (Li): (barrel diode on PBFA II)	60 eV
ion beam (p): (short focus on Kalif)	several 10's eV
x-rays (double-pinch target on Z)	70 eV
x-rays (dynamic hohlraum on Z)	215 eV

The pulsed power community has considerable expertise in diagnosing Hot Dense Matter in a harsh environment

Some Questions regarding charge to group

1. If the first 1 ns of the ion pulse meets the requirements, can the actual pulse be longer?
2. Why does it need to be repetitive? Why have multiple chambers? The HEDP experiments are single-shot experiments.
3. The neutralizing plasma near the target must be much greater than $10^{12}/cm^3$ ($n_b \sim 3x10^{14}/cm^3$ near the target)
4. Why only 5 m total length ? (huge voltage tilt)
5. Is enhanced stopping considered? (not mentioned in papers).

Ion Beam Parameters for HEDP (as suggested in the handouts)

19 MeV Ne^{+1}

$N \sim 1.4 \times 10^{13}$

$t \sim 1$ ns

$r_{spot} \sim 1$ mm

$I_{particle} \sim 2.2$ kA

~ 1 MeV/nucleon

$\beta \sim 0.05$

$L = \beta ct \sim 1.5$ cm

$E \sim 36$ J

General Comments on single-stage diodes:

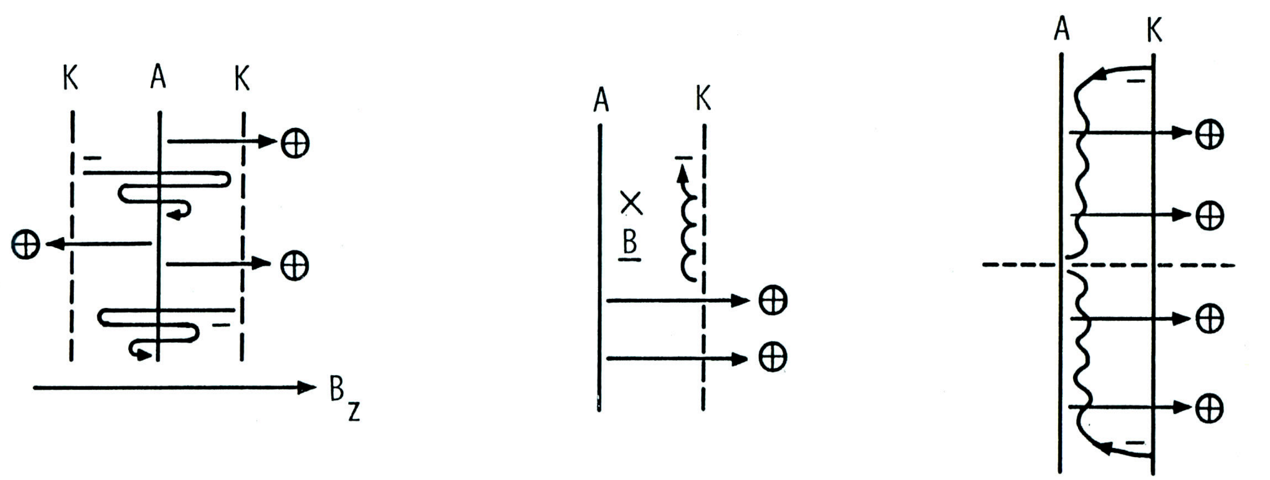
Diode types previously studied

Transverse temperatures in the Light Ion Program

Voltage accuracy needed for bunching

General comments regarding desired beam parameters for HEDP

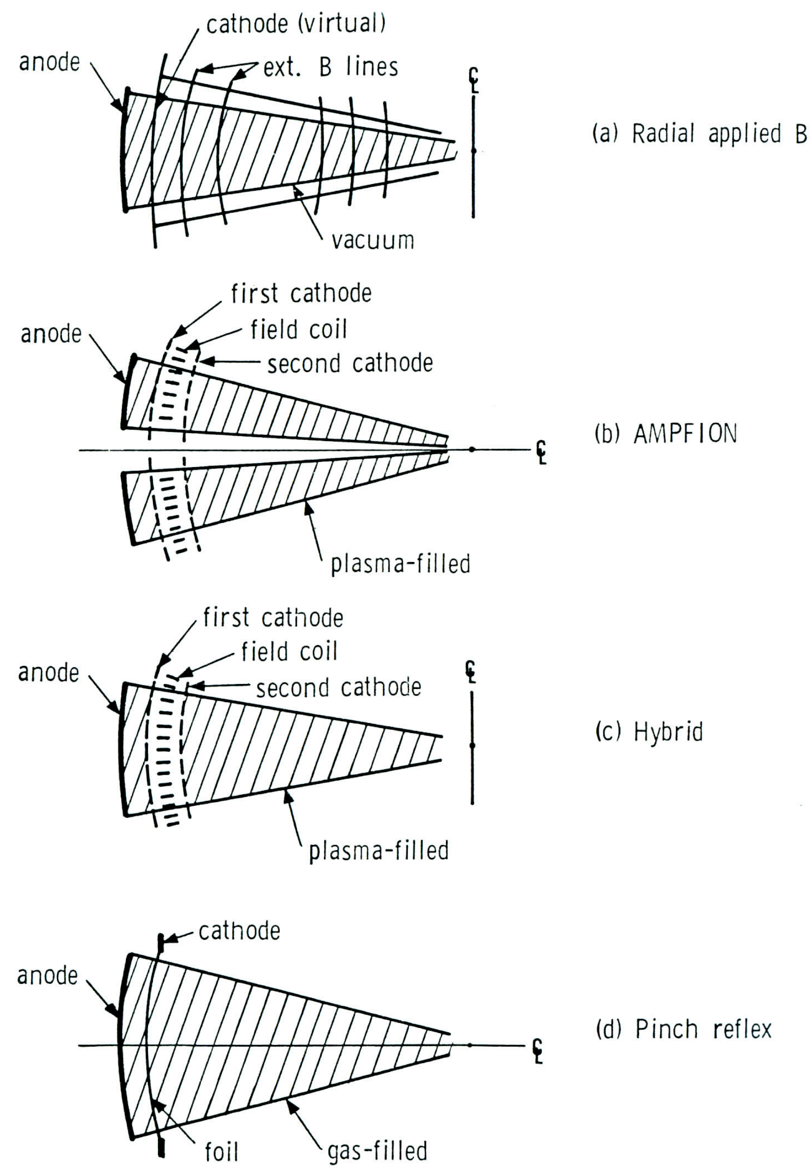
Ion diode types used in the Light Ion Fusion program



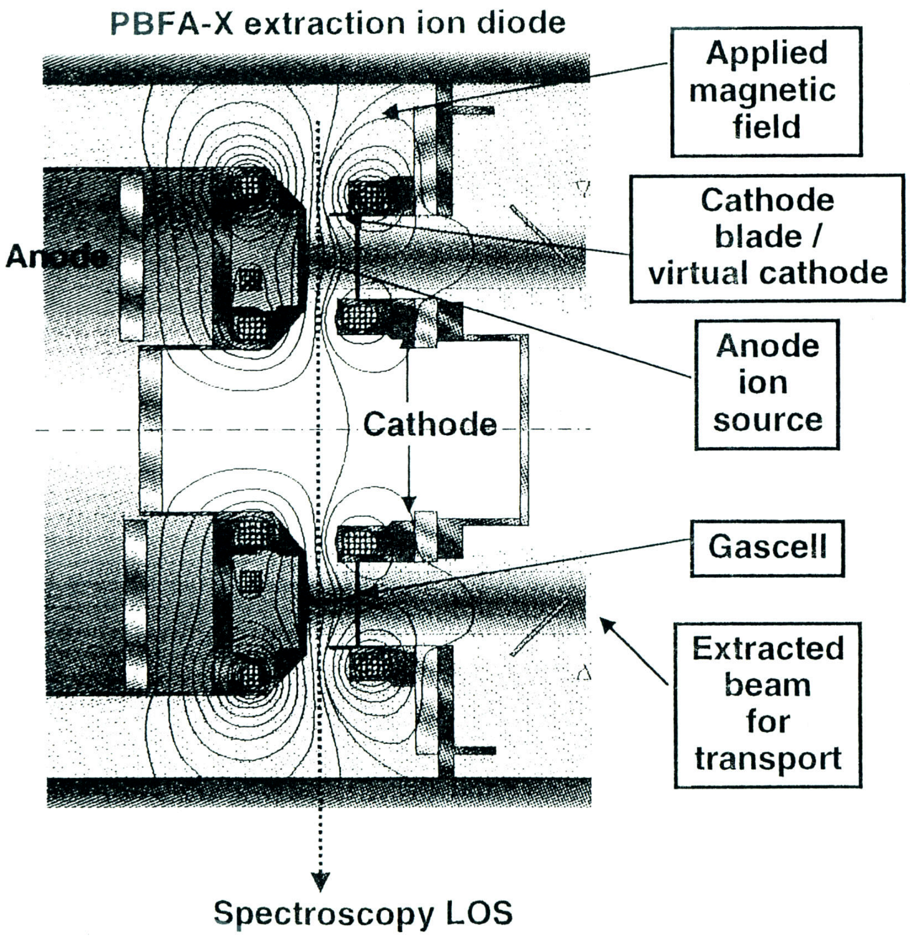
(a) Reflexing-electron (b) Magnetically-insulated (c) Pinched electron beam

In all cases, the goal was to minimize the electron current to the anode to achieve high efficiency

Several types of ion diodes were developed as part of the Light Ion Fusion program



The Extractor Diode on PBFA produced 50 kJ of Li ions



PBFA-X Li Beam	High Yield Li Beam
10 MV	30 MV
0.3 MA	1 MA
3 TW	30 TW
15 ns	40 ns
50 kJ	1.2 MJ
22 mR*	6-12 mR
0.6 kA/cm^2	1-2 kA/cm^2

Issues:
- •divergence
- •purity
- •impedance collapse
- •uniformity

Micro-divergence, parasitic load, impedance collapse

Key Issues in ion beam generation

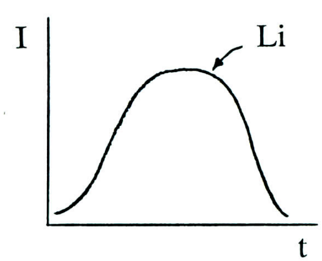
Issue 1. <u>microdivergence</u>

want $\theta_\mu \sim 6$ mrad

have $\theta_\mu \sim 20 - 30$ mrad

Issue 2. <u>parasitic load</u>

want



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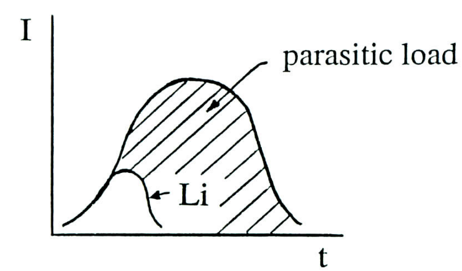
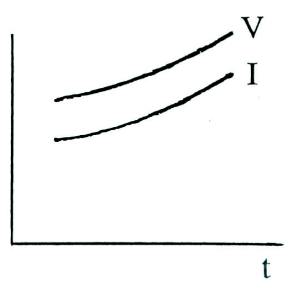


Issue 3. <u>impedance collapse</u>

want



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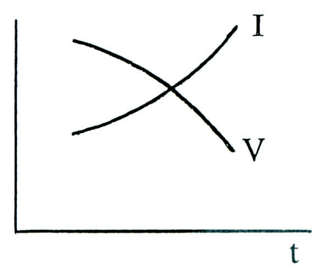
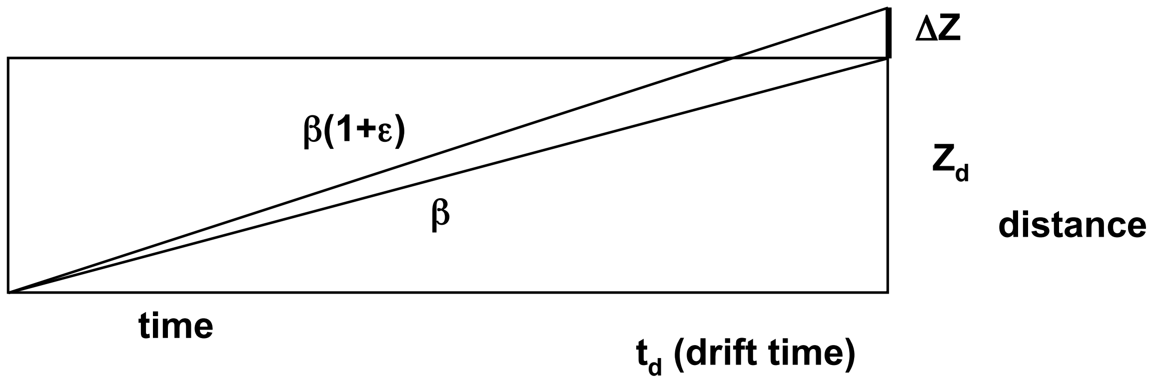


Voltage accuracy needed for bunching

$$Z_d = \beta c t_d$$
$$Z_d^* = \beta(1+\varepsilon) c t_d$$
$$\Delta Z = \varepsilon \beta c t_d = \varepsilon Z_d$$

$$\varepsilon_\beta = (\Delta Z)/Z_d$$
$$\varepsilon_{VOLT} = 2\,\varepsilon_\beta$$



Examples:	IBX	HEDP	LIF Driver	HIF Driver
	$\beta = 0.03$	$\beta = 0.05$	$\beta = 0.1$	$\beta = 0.2$
"acceptance window" ($\Delta Z = \beta c \Delta t$)	Δt = 50 ns ΔZ = 45 cm Z_d = 30 m	Δt = 1 ns ΔZ = 1.5 cm Z_d = 5m	Δt = 10ns ΔZ = 30 cm Z_d = 3 m	Δt = 10 ns ΔZ = 60 cm Z_d = 400 m
	ε_β = 45/3000 = 1.5% ε_{VOLT} = 3%	ε_β = 1.5/500 = 0.3% ε_{VOLT} = 0.6%	ε_β = 30/300 = 10% ε_{VOLT} = 20%	ε_β = 60/40000 = 0.15% ε_{VOLT} = 0.3%

General comments regarding desired beam parameters for HEDP

Shortest pulses in pulsed power accelerators are typically 10-20 ns (not 1 ns)

Ion beam transverse temperatures are sufficiently large that for ballistic focusing, very short focal lengths are required to hit a small spot (e.g., 1 mm radius)

Therefore, for drift compression, the beam must be transported at a relatively large radius, and then focused radially near the target with a focusing cell

Typical parameters for a single-stage, voltage-ramped, ion diode for the Light Ion Fusion program were only required to compress the beam by a factor of 2 or 3

All past ion diodes studied for fusion required high efficiency – for HEDP this is not a requirement. For example, the simple bi-polar diode offers the possibility of better beam quality

Possible facilities for single-stage ion diode

Mercury at NRL

Gamble II at NRL

RITS at SNL

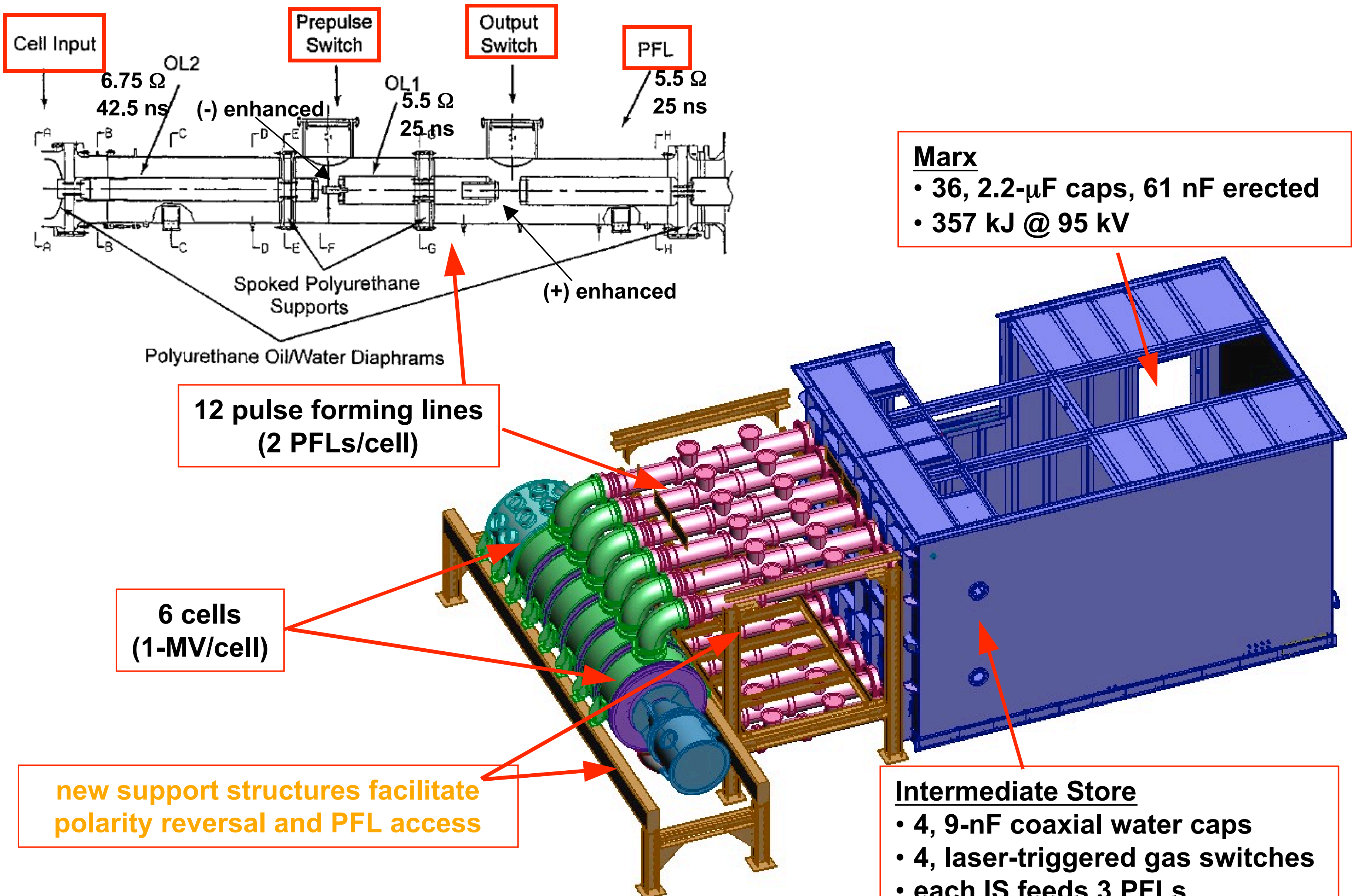
RHEPP/MAP at SNL

(Sabre at SNL was disassembled)

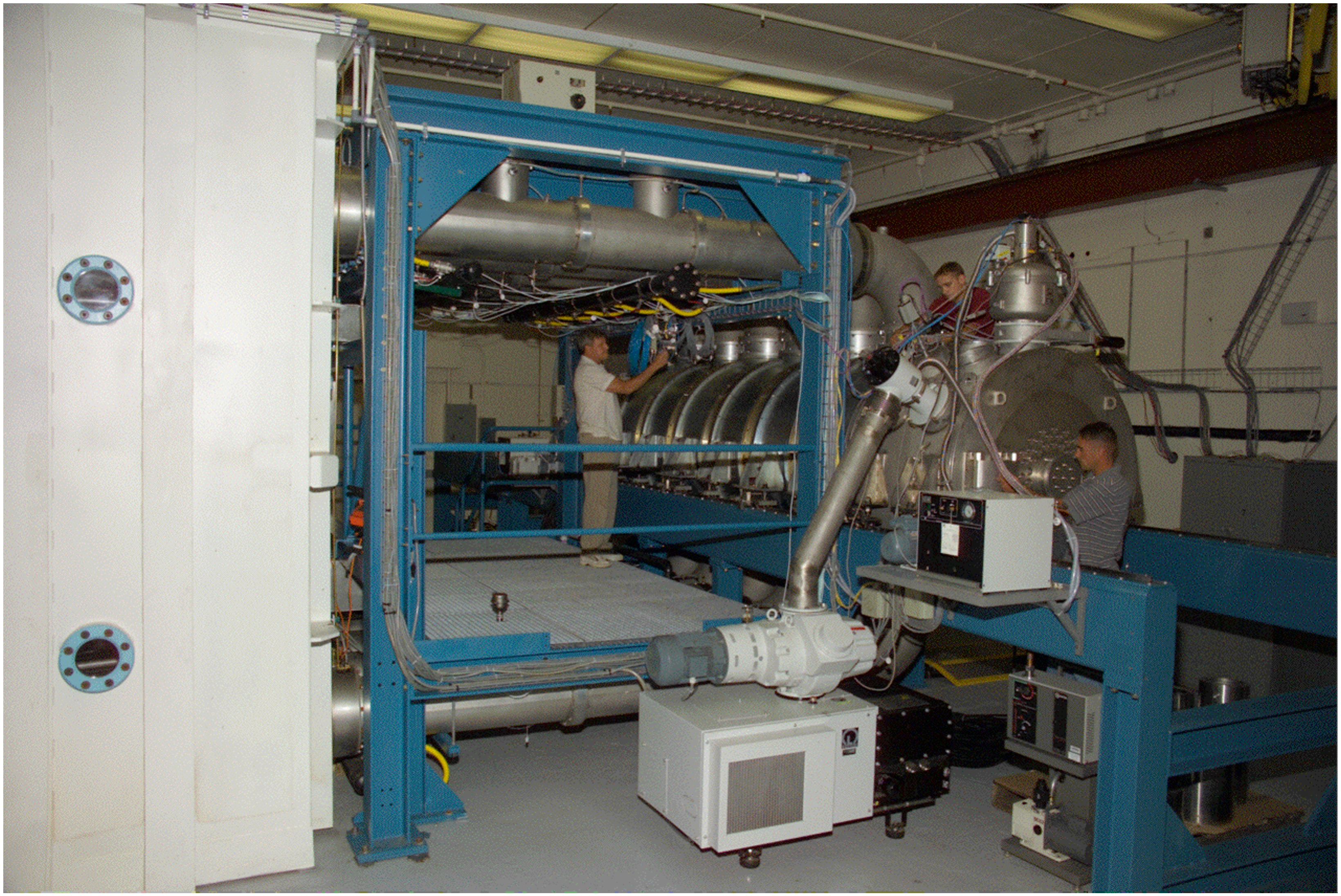
(Cobra at Cornell was modified into a z-pinch driver)

MERCURY at NRL will be operational in FY05 to produce a 6-MV, 350-kA, 50 ns pulse in either polarity

NRL

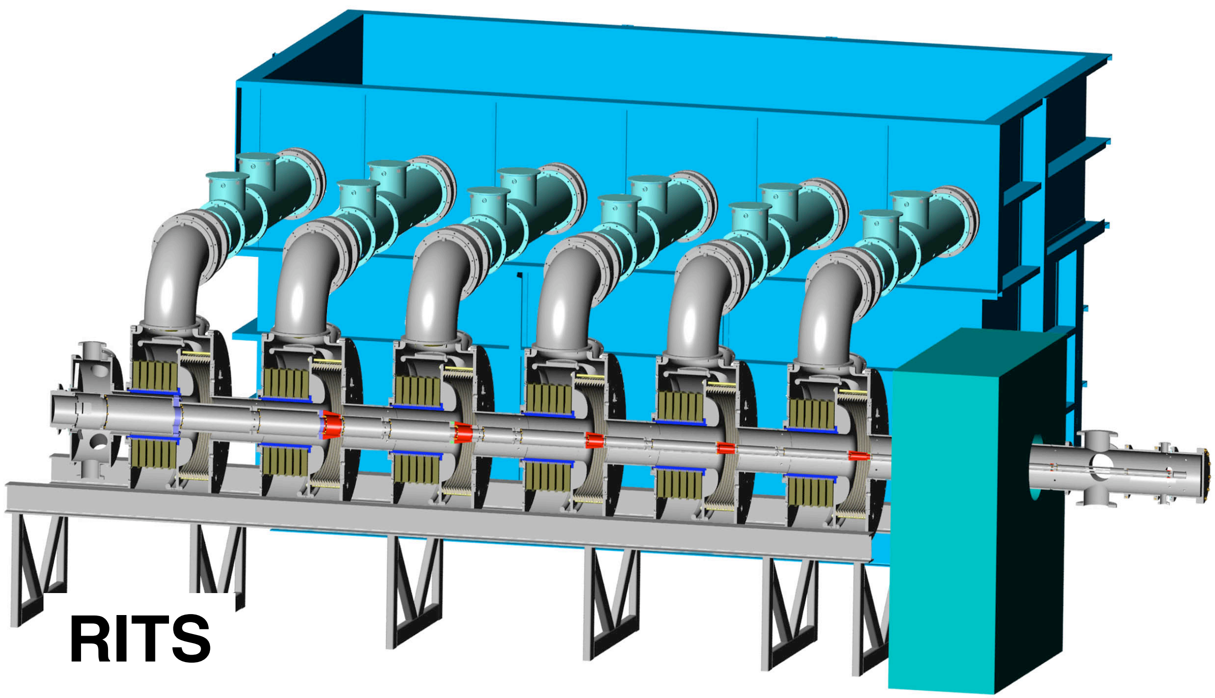


Picture of front-end of Mercury – October 2004
Assembly and pulsed power testing are near completion

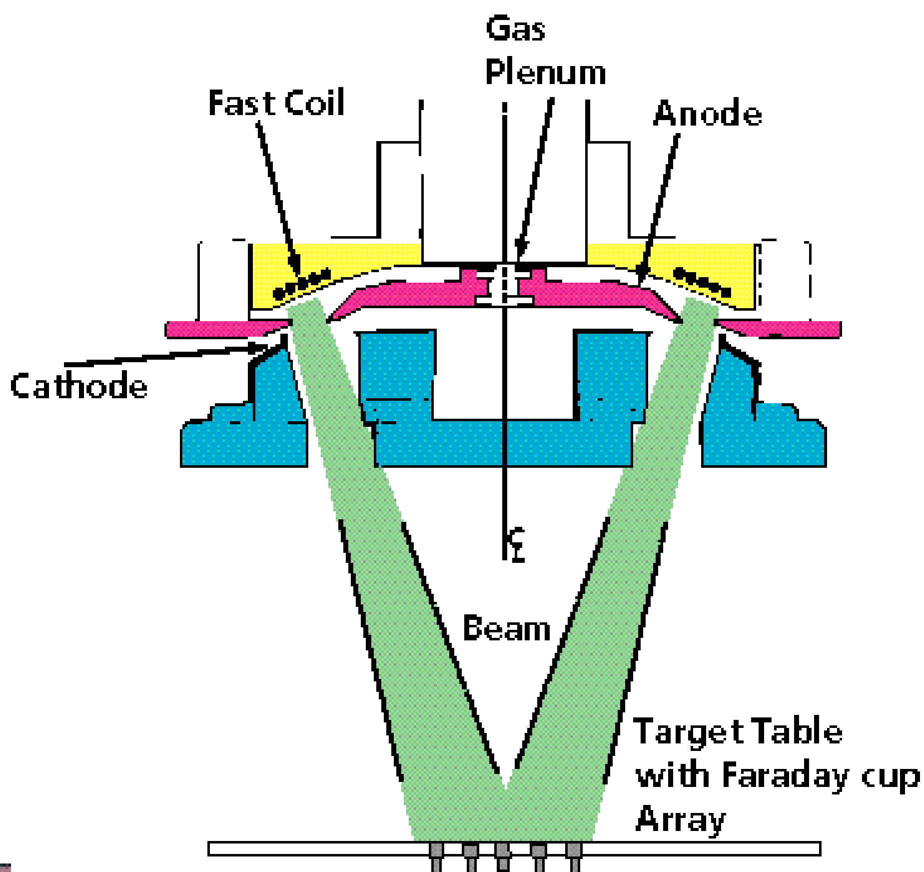


RITS (Radiographic Integrated Test Stand) at SNL was developed for advanced radiography

High intensity electron beam systems for flash x-ray radiography are presently a research topic funded by the Department of Energy. The Radiographic Integrated Test Stand (RITS) at Sandia operates at 5.5-MV, 150-kA, 60-ns pulse width in either negative or positive polarity, and is being upgraded in FY05 to 11-MV, 150-kA operation



RHEPP/MAP at SNL can generate multiple ion beams



500-750 kV

≤ 250 A/cm^2

Beams from H, He, N_2, O_2,

Ne, Ar, Xe, and CH_4 gas

Overall Treatment area

~ 100 cm^2

Diode vacuum ~ 10^{-5} Torr

Some Single-Stage Ion Diode Options:

(A) Near-term: PRD on Gamble II

(B) Longer-term: Applied-B diode with MAP (He) on Gamble II

(C) Long-term: Bi-polar diode with LTD with hot-plate source

(A) Near-term option: PRD on Gamble II

Concept is to get started doing HEDP and diagnostics ASAP

Use a PRD (Pinch Reflex Diode) on Gamble II (~ 1.5 MV proton)

Ballistically focus beam to obtain highest ion current density possible
at the focus (~ 250 kA/cm^2)

Plate at focus with hole (~ 1 mm radius)

Beamlet with 1 mm radius has ~ 7.5 kA

Beamlet energy per ns is (7.5 kA)(1.5 MV)(1 ns) ≈ 10 J/ns

Issue: Beam pulse length is 50 ns
Beam rise time is 25 ns
How to switch out a 1 ns pulse at full power?
Burn through a foil to steepen pulse?
If steepened, can a pulse longer than 1 ns be used?

(A) Near-term option: PRD on Gamble II (cont'd)

Possible Phases:

(1) Set up 1 mm beamlet

takes 1-2 weeks on Gamble II at about $45k/week (includes experimenter)

(2) Steepen pulse and test HEDP diagnostics

(3) Add a z-discharge focus cell ($\lambda/4$ or $\lambda/8$) to obtain even higher deposition

(B) Longer-term option: applied-B diode with MAP (He) on Gamble II

Higher intensities than Option (A)

Possible phases:

(1) Develop applied-B diode on Gamble II with MAP (He) ion source and slight voltage ramp (MAP source should have steep rise-time)

(2) Add a focus cell

(C) Long-term option: bi-polar diode with LTD with hot plate source

Bi-polar diode with no B-field coils
(high impedance diode, no requirement on efficiency)

20 MV

K^{+1} hot plate source

0.1 A/cm^2 (100 A total)

Diode radius ~ 20 cm, spherically-shaped section

Pulse length ~ 20 ns

Voltage ramp to bunch by a factor of 20

Drift compression (and radial ballistic compression) up to a focus cell

Focus cell ($\lambda/4$ or $\lambda/8$) down to small spot (~ 1 mm radius)

(C) Long-term option: bi-polar diode with LTD with hot plate source

(cont'd)

Possible phases:

(1) Develop high impedance LTD-IVA with Bi-Polar diode with hot plate source to test drift compression at 1-2 MV

(2) Extend (1) to higher voltage (20 MV)

(3) Add a final focus cell

Ionization Front Accelerator (IFA) option

IFA Concept and features – ions already bunched radially and longitudinally

Past IFE experiments successful (IFA-1 and IFA-2)

Scaling and examples for HEDP and HIF

What is new: high power short pulse lasers as needed for the IFE are available now

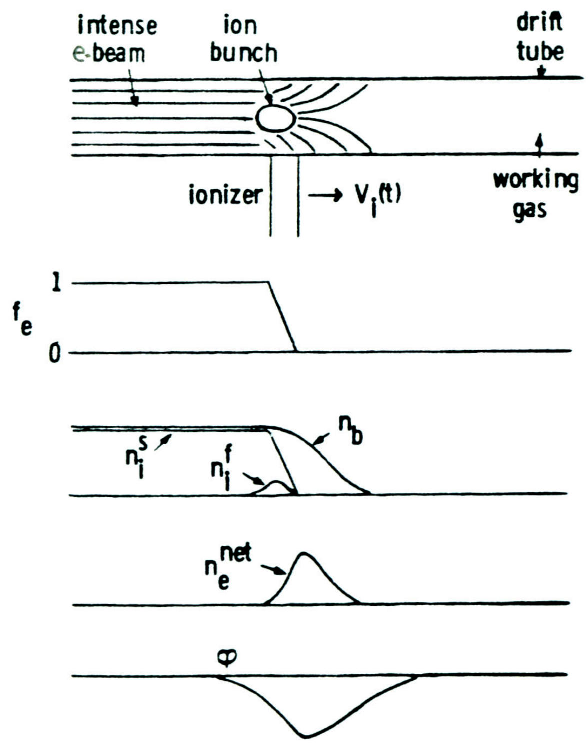


Figure 1 Ionization Front Accelerator.

Experimental Demonstration of Controlled Collective Ion Acceleration with the Ionization-Front Accelerator

C. L. Olson, C. A. Frost, E. L. Patterson, J. P. Anthes, and J. W. Poukey
Sandia National Laboratories, Albuquerque, New Mexico 87185
(Received 25 November 1985)

Experiments with a second-generation collective ion accelerator (IFA-2) are reported. Results demonstrate that ion acceleration with fields of 33 MV/m over 30 cm has been achieved with a controlled collective accelerator for the first time.

PACS numbers: 52.75.Di, 29.15.Dt, 41.80.Dd, 84.70.+p

In collective accelerators,[1-3] the collective fields of an ensemble of charged particles are to be used to accelerate a smaller group of charged particles, usually of a different species. In this manner, collective accelerators may produce accelerating fields orders of magnitude higher than those in conventional accelerators. However, the quest for a scalable, working, collective accelerator has proved to be elusive for many years. In the ionization-front accelerator (IFA), the large space-charge field of an intense relativistic electron beam (IREB) is accurately controlled with a laser to produce high-gradient ion acceleration.[1,4,5] We report here the successful operation of a second-generation collective accelerator system (IFA-2) which demonstrates that particle acceleration with accelerating fields of 33 MV/m over 30 cm has been achieved with a controlled collective accelerator for the first time.

To show that large space-charge fields are possible with an IREB, consider first a long electron beam of uniform density n_e and radius r_b. The beam appears as

is swept, it ionizes the working gas, creating a plasma of density $n_p \approx n_e$. The plasma electrons are expelled radially by the IREB space-charge field, leaving a plasma ion background density $n_p^i \approx n_e$ to provide charge neutrality for the IREB. The IREB propagates quickly through the charge-neutralizing plasma region; just ahead of the plasma region the IREB is subjected to its own space-charge field and diverges radially again. The strong potential well associated with the space charge at the head of the IREB follows the moving laser front synchronously. Ions (produced, e.g., by IREB-induced ionization of a light-ion–source gas mixed with the working gas) are trapped in the potential well and experience acceleration as the laser sweep accelerates.

The IFA is a direct extension of the natural collective acceleration process that occurs when an IREB is injected into a low-pressure neutral gas.[1,8-10] In the natural process the potential well elongates, has a relatively small axial electric field, and moves at constant

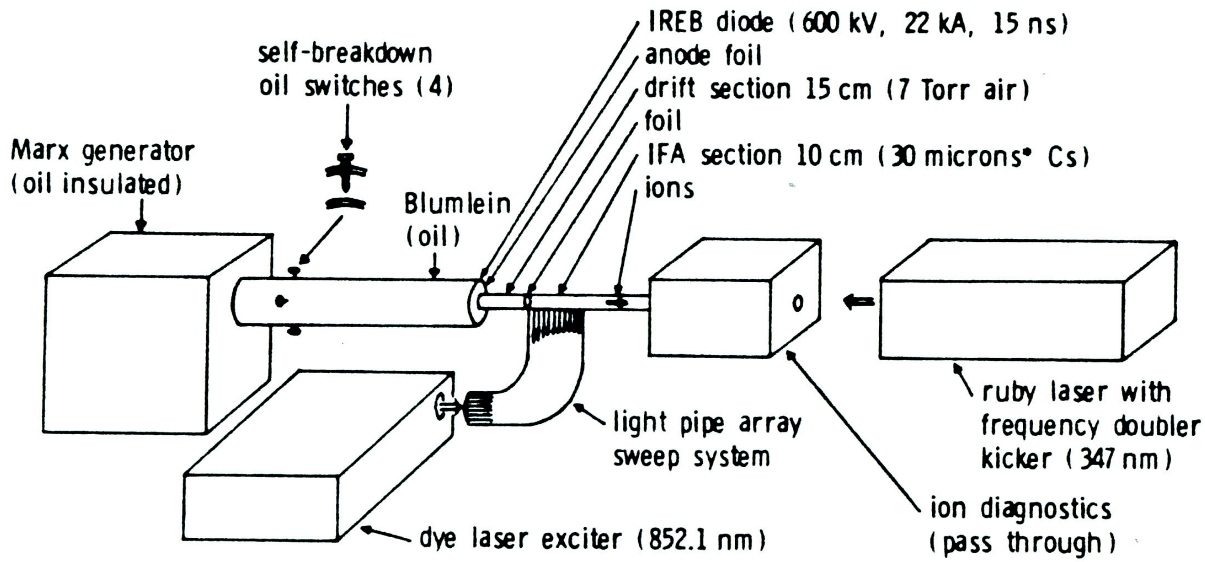


Figure 3. IFA-1.

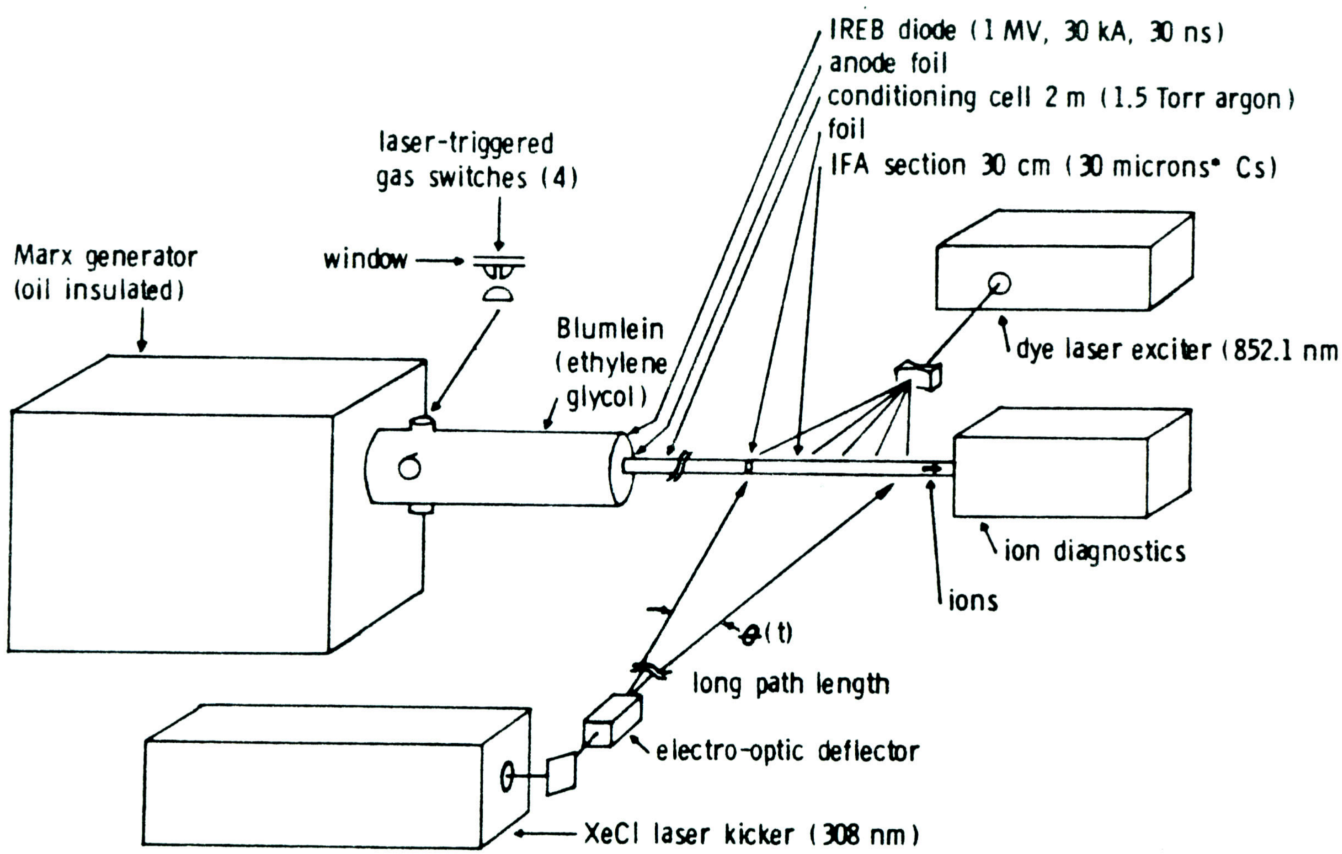


Figure 4. IFA-2.

The IFA intrinsically generates a sub-nanosecond ion pulse, as shown in these examples for a small e-beam driver

TABLE 5

IFA Example: Feasibility (20 MeV Protons)

IREB	$\mathcal{E}_e$	600 keV
	I_o	20 kA
	τ	> 10 nsec
	r_b	0.5 cm
	$\mathcal{P}$	1.3×10^{10} W
	$\mathcal{E}_b$	>130 J
DRIFT	ℓ	20 cm
	E_o	10^6 V/cm
	p	0.003 Torr
	$\mathcal{E}_{IONIZE}$	6×10^{-5} J
LIGHT	$\mathcal{J}_1$	10^7 W
	τ_1	1 nsec
	$\mathcal{E}_1$	0.01 J
	$\mathcal{J}_2$	1.5×10^8 W
	τ_2	10 nsec
	$\mathcal{E}_2$	1.5 J
PROTONS	$\mathcal{E}_i$	20 MeV
	N	10^{12}
	$\mathcal{P}$	3×10^{10} W
	T	0.1 nsec
	$\mathcal{E}$	3 J

TABLE 6

IFA Example: 1 GeV PROTON

IREB	$\mathcal{E}_e$	2 MeV
	I_o	30 kA
	τ	75 nsec
	r_b	1 cm
	$\mathcal{P}$	6×10^{10} W
	$\mathcal{E}_b$	4.5 kJ
DRIFT	ℓ	10 meters
	E_o	10^6 V/cm
	p	0.003 Torr
	$\mathcal{E}_{IONIZE}$	0.006 J
LIGHT	$\mathcal{J}_1$	10^9 W
	τ_1	1 nsec
	$\mathcal{E}_1$	1 J
	$\mathcal{J}_2$	1.5×10^8 W
	τ_2	75 nsec
	$\mathcal{E}_2$	11 J
PROTONS	$\mathcal{E}_i$	1 GeV
	N	3×10^{12}
	$\mathcal{P}$	10^{13} W
	T	0.03 nsec
	$\mathcal{E}$	500 J

TABLE 7

IFA Example: 50 A MeV $^{238}_{92}U^{60+}$

Heavy ion example

IREB	$\mathcal{E}_e$	1 MeV
	I_o	30 kA
	τ	50 nsec
	r_b	1 cm
	$\mathcal{P}$	3×10^{10} W
	$\mathcal{E}_b$	1.5 kJ
DRIFT	ℓ	200 cm
	E_o	10^6 V/cm
	p	0.003 Torr
	$\mathcal{E}_{IONIZE}$	0.0012 J
LIGHT	$\mathcal{J}_1$	1.5×10^8 W
	τ_1	1 nsec
	$\mathcal{E}_1$	0.15 J
	$\mathcal{J}_2$	1.5×10^8 W
	τ_2	50 nsec
	$\mathcal{E}_2$	7.5 J
$^{238}_{92}U^{60+}$ IONS	$\mathcal{E}_i$/A	50 MeV
	N_ζ	3×10^{12}
	$\mathcal{P}$	10^{12} W
	T	0.1 nsec
	$\mathcal{E}$	100 J

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- General comments on single-stage diodes
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- Single-stage diode options (three) proposed
- Ionization Front Accelerator (IFA) option proposed