### Title

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### Authors

Staples, John W.
Sessler, Andrew
Keller, Roderich
et al.

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# RF-Based Accelerators for HEDP Research [*]

John W. Staples, Andrew Sessler, Roderich Keller, LBNL, Berkeley, California,
Petr Ostroumov, ANL, Argonne, Illinois, Weiren Chou, Fermilab, Batavia, Illinois

## *Abstract*

Accelerator-driven High-Energy Density Physics (HEDP) experiments require typically 1 nanosecond, 1 microcoulomb pulses of mass 20 ions accelerated to several MeV to produce eV-level excitations in thin targets, the “warm dense matter” regime. Traditionally the province of induction linacs, RF-based acceleration may be a viable alternative with recent breakthroughs in accelerating structures and high-field compact superconducting solenoids. A reference design for an RF-based accelerator for HEDP research is presented using 15 T solenoids and multiple-gap RF structures configured with multiple parallel beams combined at the target. The beam is ballistically compressed with an induction linac core providing the necessary energy sweep and injected into a plasma-neutralized drift compression channel resulting in a 1 mm radius beam spot 1 nanosecond long at a thin foil or low-density target.

## INTRODUCTION

Warm dense matter (WDM) is defined as that state existing with densities of 0.001 to 10 grams/cm$^3$ and thermal energy of 0.1 to 10 eV. WDM exists in the cores of large planets, in X-ray driven inertial confined fusion and in systems transitioning from solid to plasma during heating. Codes that simulate WDM conditions produce results in conflict with each other, so experimental data is need to benchmark and improve the codes. As a solid is turned into a plasma by laser or X-ray heating, ion stopping by free electrons is different from that of bound electrons, and $dE/dx$ in the material is not accounted for correctly.

Experimental investigation of WDM may be carried out by illuminating thin foils with nanosecond light ion (A $\approx$ 20) beams and observing the plasma. Thin foils are desirable so the energy of the heating beam is not diminished significantly in the interaction volume and that $dE/dx$ does not vary significantly in the sample. Recently, experimental verification of many of the techniques needed to accelerate, time compress and space-charge neutralize low charge state microcoulomb beams has been demonstrated [1].

RF-based accelerators may offer a more economical solution than induction linacs for accelerating one microcoulomb light ion beams and focusing them down to a 1 mm spot radius and a 1 nsec pulse length (1 kA peak current).

This paper summarizes the results of a workshop held at LBNL in October, 2004 in which the science of WDM and several accelerator-based scenarios of producing suitable beams were presented [2].

## SCHEMES CONSIDERED

Several approaches to RF-based acceleration were considered for accelerating a singly-charge neon beam to a final energy of 20 MeV (1 MeV/n). In all cases, the compression down to the 1 nanosecond final pulse length is critical and imposes severe constraints on the uncorrelated energy spread of the beam from the accelerator. Most schemes were abandoned for reasons indicated below.

### *Conventional Drift-Tube Linac*

A conventional quadrupole-focused drift tube linac for a single-charged neon ion requires approximately 13 meters on 100 MHz linac with a peak accelerating gradient of 2 MV/m in the gaps. Peak quadrupole field limitations of 20 kG/cm, probably above the technological limit, require a very high energy preinjector, at least 2 MV, and also require a low-periodicity FFFDDD focusing period to attain sufficient focusing of a 200 emA beam 5 microsecond long. The ballistic compression to 1 nanosecond requires an uncorrelated energy spread unattainable in such a design, also the severe focusing requirement and high preinjector voltage, led us to abandon this design.

### *Long Drift Tubes with Pulsers*

Instead of an RF-based linac, a *single* 1 microcoulomb bunch can be accelerated through long drift tubes, each supplied by a pulser in the megavolt range. (The focusing scheme was not considered in this scenario.) By applying a slight tilt to the gap field, a degree of compression may be achieved during acceleration, not possible with a conventional RF-based accelerator. With a 1 MV singly-charged neon preinjector and 500 kV gap voltages, 20 MeV is achieved in 57 meters with 38 drift tube/pulser modules. As the beam accelerates, it shortens, but the drift tubes lengthen due to the velocity, and the most significant contributor to the drift tube length is the risetime of the pulsers, assumed to be 100 nsec for this exercise. (The pulse must remain in each drift tube for the duration of the risetime of the pulser added to the transit time of the entire pulse through the drift tube.) This scheme may have some merit, but was not explored further.

### *RF Spiral Structure*

A spiral structure, such as found in traveling-wave tubes, carries a longitudinal E-field that will accelerate a beam.

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The pitch angle of the spiral is determined by the beam velocity, which starts off relatively low. For a 1 MV injector, the initial velocity of a singly-charged neon is $\beta = v/c = 0.01$ several turns per millimeter are required. The longitudinal field on axis is $E_{z,wall}\mathrm{I1}(ka)$, where $k = 2\pi/\beta\lambda$ is the wavenumber and $a$ is the wall radius. To minimize the attenuation of the longitudinal wall field to the beam axis, $ka < 1$, which limits the radius to a few centimeters, or the frequency to a few Megahertz. These limitations limit the peak accelerating field or aperture radius needed for the bunch charge required so this approach was abandoned.

### *Pulsed Waveform Spiral Structure*

Instead of supplying a spiral with RF, a shaped accelerating pulse may be used to accelerate a single bunch, so the spectral components are limited to a lower frequency cutoff. This approach is described by Briggs [3] in another paper at this conference and has promise.

### *Stacking Ring*

A long (5 microsecond) pulse may be partially compressed in a stacking ring and then kicked out in a single turn. The beam is painted in both transverse planes and a barrier-bucket RF system keeps the extraction gap clean. The extracted beam is further compressed with an externally supplied energy tilt, supplied by an induction linac or very low frequency RF cavity.

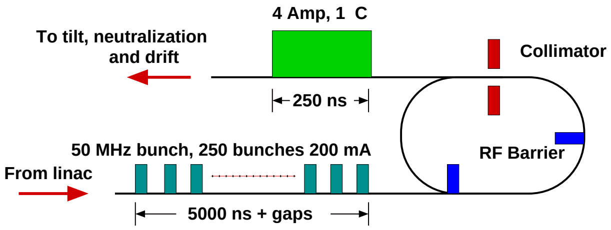

Figure 1: Stacking Sequence

To accumulate 1 microcoulomb, 250 bunches from a 200 mA, 50 MHz linac are betatron stacked in a 12 meter circumference ring over a period of about 10 turns, similar to the CERN CLIC stacking process, as shown in Figure 1. The bunches are chopped and timed so that an extraction gap is present for a transverse kicker. The circulating beam current immediately after stacking is 2 amperes, with a 500 nsec pulse length. The tune depression of this beam with 1 microcoulomb of singly-charged neon is only about 0.3, and the entire stacking and extraction process takes place in 5 microseconds, short enough so that intra-beam scattering or other collective effects will not be significant.

Although the stacking and extraction issues seem tractable for this scenario, the transport of a single 500 nanosecond, 2 ampere beam for even a short distance results in a too large energy spread even before an energy tilt can be applied for ballistic compression and transport in a plasma-neutralized transport channel to the target. A time compression of a factor of 500 requires an initial energy spread of less than 1/500 (0.2%), and significantly less for a realistic final focus system. Hence, this approach was abandoned.

## PARALLEL BEAM CONFIGURATION

### *Parallel Beams*

The most promising RF scenario of providing a microcoulomb of 20 MeV neon, compressed to 1 nsec at the target, is to accelerate a number of parallel beams, (say) 16, with low frequency (50 MHz) room-temperature structures, each supplying about 1 MV of voltage gain, interspersed with very high field (15 Tesla) superconducting solenoids.

A multi-aperture ion source would provide 16 beams of singly-charged neon, each 500 emA, to a segmented 2 MV column. The beam would be klystron bunched and accelerated to 20 MeV. An energy chirp would be applied at the linac exit and the beams then ballistically compressed in a plasma-neutralized channel to converge onto a target.

The availability of high-field solenoids opens up interesting possibilities of focusing high-intensity low-charge-state beams that cannot be managed with normal-conducting quadrupoles.

### *Ion Source*

The primary goal for the ion source under the linac scenario is to deliver a total Ne$^{1+}$ beam current of 8 A through 16 channels to the main rf accelerator at 2 MeV energy, with a pulse length of 200 ns. Following scaling laws discussed in [4] it turns out to be convenient to extract these 16 beams at 100 kV only and then accelerate them in parallel electrostatic channels. Each of the 16 main beams will actually be composed of 7 beamlets, extracted from a concentric aperture pattern, and with pulsed extraction, the gap width d for these 200 ns pulses can be reduced to 0.7 times the width necessary for d. c. conditions.

For 100 kV extraction voltage and an aspect ratio S = r/d = 0.5 for each extraction gap, each beamlet carries 74.4 mA of current, and the aperture radius is 4.95 mm. With an initial divergence half-angle of 20 mrad, this leads to an un-normalized, encompassing r/r' emittance of 297$\pi$ mm mrad and, by applying the commonly accepted reduction factor of 8 (4 for 4-rms to 1-rms and 2 for r/r' to x/x'), to a normalized 1-rms x/x' emittance of $\epsilon_{7,n}$ = 0.121 $\pi$ mm mrad. The current density necessary to yield 74.4 mA of beamlet current is 96.7 mA/cm$^2$, well in range for filament-sustained plasma discharges. The extension of the extraction system to a full-energy 2-MV accelerating column is straightforward.

For the plasma generator, a large discharge chamber is chosen, lined with permanent cusp magnets, see an example for 16 beams in Fig. 2. A pulsed gas valve feeds neon into the chamber from the backside, and a diverter speeds up the establishment of uniform pressure across the chamber. Sixteen thermionic filaments (Ta or W) are inserted

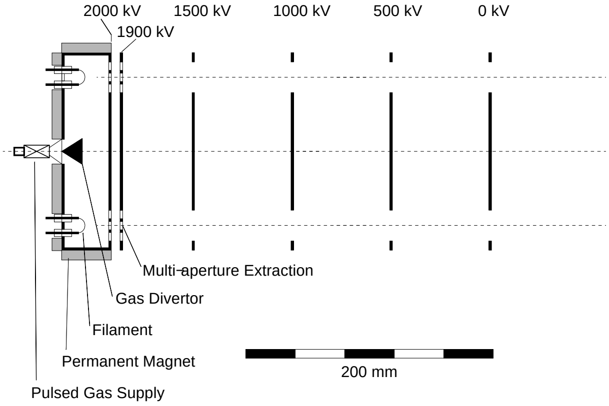

Figure 2: Schematic of a multi-cusp ion source with multi-aperture, multi-gap extraction system. There is a total of 112 beamlets, grouped into 2x8 channels of 7 beamlets, each. The illustration shows a section of the narrow side view, with two beam channels.

into the chamber backside and operated in d. c. mode to best avoid the effects of temperature shocks. A low-power pre-ionization discharge of about 5 microsec duration is ignited to facilitate a fast rise time of the main discharge pulse that will have a duration of about 250 ns to offer a sufficiently long flat-top time for beam-pulse generation.

## *Accelerating Cavities*

Experiments with IH resonators at CERN showed the possibility of obtaining high electric fields in IH resonators [5]. At 200 MHz the maximum effective accelerating gradient was 10.7 MV/m. This corresponds to a local field maximum of 75 MV/m, and to fields in excess of 50 MV/m (3.5 times the Kilpatrick limit) on large portions of the drift tube surfaces. The pulse length in this experiments was in the range from 100 microsec to 1 ms.

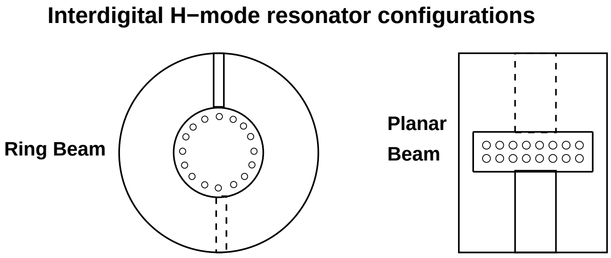

Figure 3: Multi-beam RF Linac

For the HEDP driver application 50 MHz 3-gap IH-resonators can be effectively applied. The accelerating gap length depends on the beam velocity and will be in the range of ∼2-5 cm. At low frequency the Kilpatrick limit weakly depends on the gap length and it is 9.5 MV/m for 50 MHz and gap length ∼2 cm. The CERN IH resonator has small diameter drift tubes therefore the total surface area under high electric field is small. In the HEDP driver resonator the surface area is much larger due to the multi-channel feature. On the other hand the pulse length can be very short and close to the resonator filling time which is ∼20 microsec for $Q_0$ =3000. We assume peak surface field in the HEDP resonators less than ∼3.2 Kilpatrick limit which is slightly lower than in the CERN IH resonator. This assumption results in a peak surface field of 30 MV/m and average field in the gap ∼18 MV/m. The energy transferred to beam is less than 10% of the stored energy in the cavity. Figure 3 shows the IH resonator designed for 100 keV/u and 1 MeV/u ion beam. Large-surface drift tubes are suitable for locating 16 beam apertures in two rows or in a ring. The surface area of the drift tube is 90x18 cm$^2$ which is sufficient to locate 2 rows of aperture holes, 8 holes in each row.

## *Solenoid Focusing*

High-field superconducting solenoids may open up new opportunities in the development of high-current linear accelerators for heavy ions. Substantial fractions of an ampere may be transported without significant emittance growth, envelope breathing is reduced to that in quadrupole channels and alignment tolerances are relaxed.

For example, a 500 mA, 20 MeV Ne$^{1+}$ beam in a lattice of 25 cm long accelerating structures and 15 cm long 15 T solenoids transport contains the beam with no envelope oscillations with a 5 rms emittance radius of 0.75 cm, as shown in Figure 4. In an equivalent FDO structure, (quad doublets, each 220 T/m and 7.5 cm long) the beam envelope flutter and breathing require twice the aperture, with an equivalent pole-tip field of 3.3 Tesla at 1.5 cm.

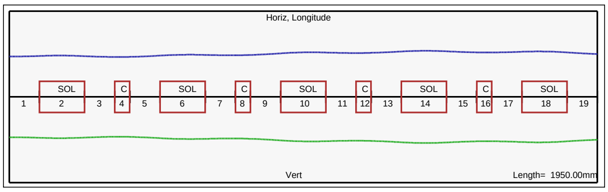

Figure 4: 500 mA 20 MeV Ne$^{1+}$ Beam in 15 T, 15 cm solenoid lattice separated by 25 cm including accelerating cavities.

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