RF Accelerator Working Group Summary

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Introduction

Current efforts in the US on inertal fusion are focused on achieving ignition at the National Ignition Facility (NIF) at LLNL using high-power lasers and indirect-drive hohlraum targets. We note that technical activity in heavy-ion fusion started in the US in 1976 and was based on the successful application of RF-accelerator and induction accelerator [1] technology. Since then the US efforts in Heavy Ion Fusion (HIF) have focused primarily on induction linac technology while RF accelerator driven systems have been pursued primarily in Europe and Japan. The most significant RF accelerator based concept and supporting study was last completed in 1998 for the European Heavy Ion Driven Inertial Fusion (HIDIF) collaboration [2]. The goal of the study, carried out within the framework of a European study group, was to demonstrate the feasibility of an RF linac and storage ring based scheme for high-repetition rate (~10 Hz) ignition with an indirectly driven low-gain target using ballistic focusing. Not much in the way of detailed system or concept studies for RF drivers has been done since, although more recently a single-pass RF-accelerator concept eliminating the use of storage rings has been proposed by Fusion Power Corporation [3]. However, significant progress has been made in the last decade in RF accelerator technology and in the physics of intense beams (including electron cloud and ion lifetime effects) that warrants examination of past efforts and a look at new possibilities to use RF accelerators in the near-term future for energy production. Other progress of significance includes the construction of the €1 Billion FAIR Project at GSI [4] and their ongoing work to improve ion-source performance and beam brightness for high charge states, as well as the application of superconducting technology at the Michigan State University Facility for Rare Isotope Beams (FRIB) [5]. It is also noteworthy to point out that increased understanding of plasma-neutralized compression and final focusing from the ongoing program in beam-driven Warm Dense Matter (WDM) has made it likely that future system studies for HIF will consider lower kinetic energy but high-current beams on target when exploring architecture optimization.

The charge to the working group included defining the requirements and constraints for applying RF accelerators to HIF, assessing the state of the technology in light of new developments since 2000, and exploring a specific design approach, if possible. Our discussions touched on all of these. We also discussed intermediate steps of R&D demonstrations vs. full-scale energy productions systems, new approaches vs. scaling present technology, strategies to move HIF forward, and associated funding issues.

We chose to focus primarily on what is needed to produce energy while defining some enabling R&D issues that still need to be addressed.

Information and statements from the plenary talks was also used to guide our discussions:

- All target options assume multiple beams.
- Need >90% plant availability.
- Effort should be made to reduce the costs of accelerator driver systems.
- P. Spiller – HIDIF is very complicated (see Fig. 1). (There are many injectors, linacs, funneling, other beam manipulations), and the RF approach would benefit from simplifications.
- P. Spiller – The requirement of 10^{15} ions/pulse starting with a small number of beams and achieving the required macropulse at the target is very challenging.
- Desorption/beam losses are still an issue in synchrotrons/storage rings – Will this also be the case for RF linacs?
- P. Spiller – Beam loss tolerances due to activation are less restrictive for ion beams vs. protons (for ions can tolerate >>1 W/m).
- R. Burke – "Present RF linac technology can meet requirements without more relaxed target requirements."
- Driver energy in the range of 1 MJ – 7 MJ covers most target designs.
- Target design advances could influence a new baseline concept.

Target requirements were provided by John Barnard (LLNL). The target details were discussed and it was acknowledged that significant effort would be needed to look at target/driver matches. The consensus of the working group members was that we could not accomplish this in the short time available to us.

Several past studies were considered that set the context for future work. These included the 2004 HEDP Workshop RF Working Group Front-End Concept [6], the HIDIF study, the 2005 ITEP High-Energy (100-GeV U) Concept [7], and the Fusion Power Corporation Single-Pass HIF Driver Concept [8]. The Single-Pass HIF Driver Concept was discussed in considerable detail.

HIDIF/FAIR

Since significant work has been done by the HIDIF study group, it was only natural to ask one of the main participants of that effort to comment on what the perceived critical issues that should be discussed might be. Prof. Ingo Hoffman (GSI), unable to attend the workshop, was so kind as to provide these comments:

> "In most general terms, I believe the critical themes after HIDIF are listed below. Some of them actually are much clearer now, thanks to the development of FAIR (Peter Spiller's field). One needs to keep in mind that a fusion driver with its tens of megawatts of heavy ion beam power cannot easily be scaled up from proton drivers. So attention should be given to the differences.
>
> - Activation with low energy heavy ions: meanwhile understood much better due to the work of I. Strasik and E. Mustafin in the context of FAIR.
> - Desorption with heavy ions: beam scrubbing effects seem to be important and helpful - Peter Spiller would know everything relevant about this.
> - Final compression: The task was not really doable largely due to the indirectly driven target of HIDIF with its very high power requirement."

These comments were noted and some discussion followed regarding recent results indicating that beam loss requirements for heavy ions (based on GSI/FAIR results) are much relaxed as compared to the 1 W/m requirements typically assumed for hand-on maintenance in high-power proton accelerators. These relaxed requirements improve chances for success for high-current RF ion accelerators (see Fig. 2) in the operating range required for HIF. The HIDIF results were also acknowledged as an important technical baseline. It was noted that today the initially proposed linac length could be reduced by up to 25% by using room-temperature IH structures rather than an Alvarez drift-tube linac. Present high-charge state ion source reliability and beam quality (emittance) continue to be issues (based on GSI experience). A cost for the HIDIF scheme (see Fig. 1) was never developed and therefore provides no cost baseline to compare new designs, however it may be possible to extrapolate costs from the earlier HIBALL-II study [9].

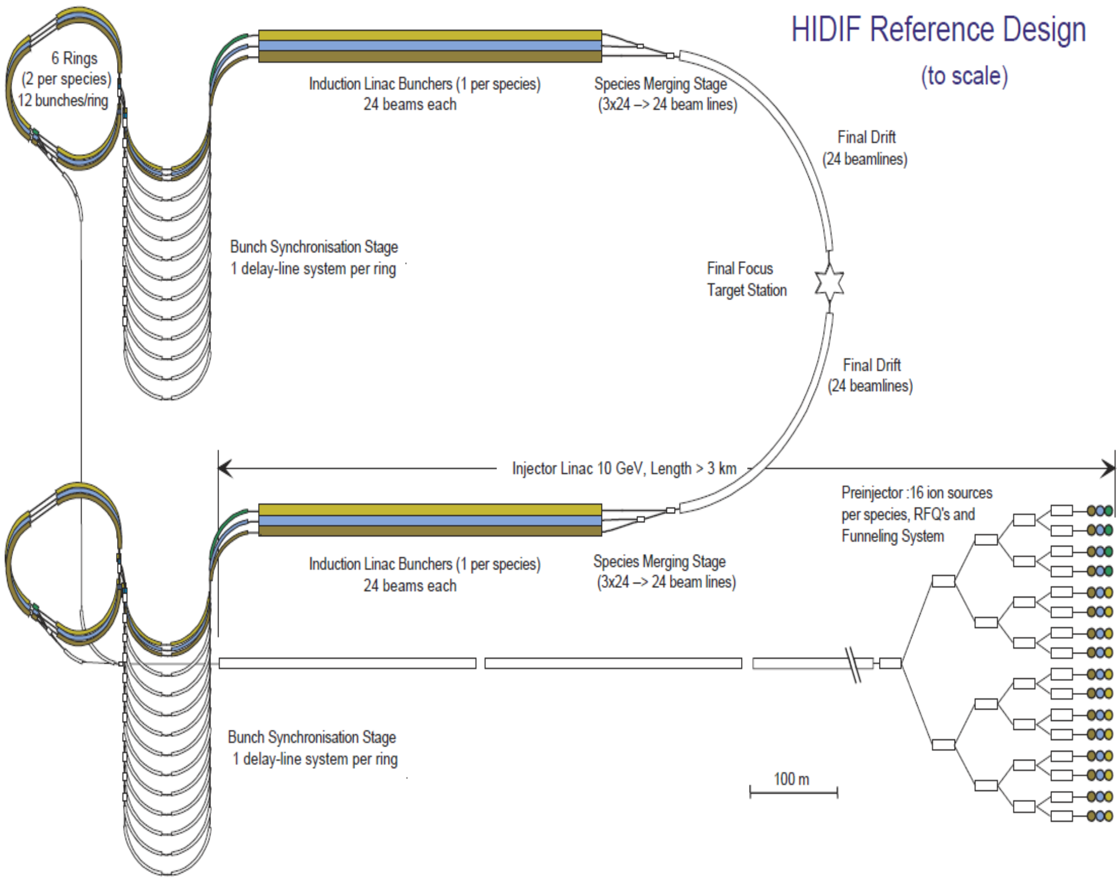

Figure 1: HIDIF Reference Design.

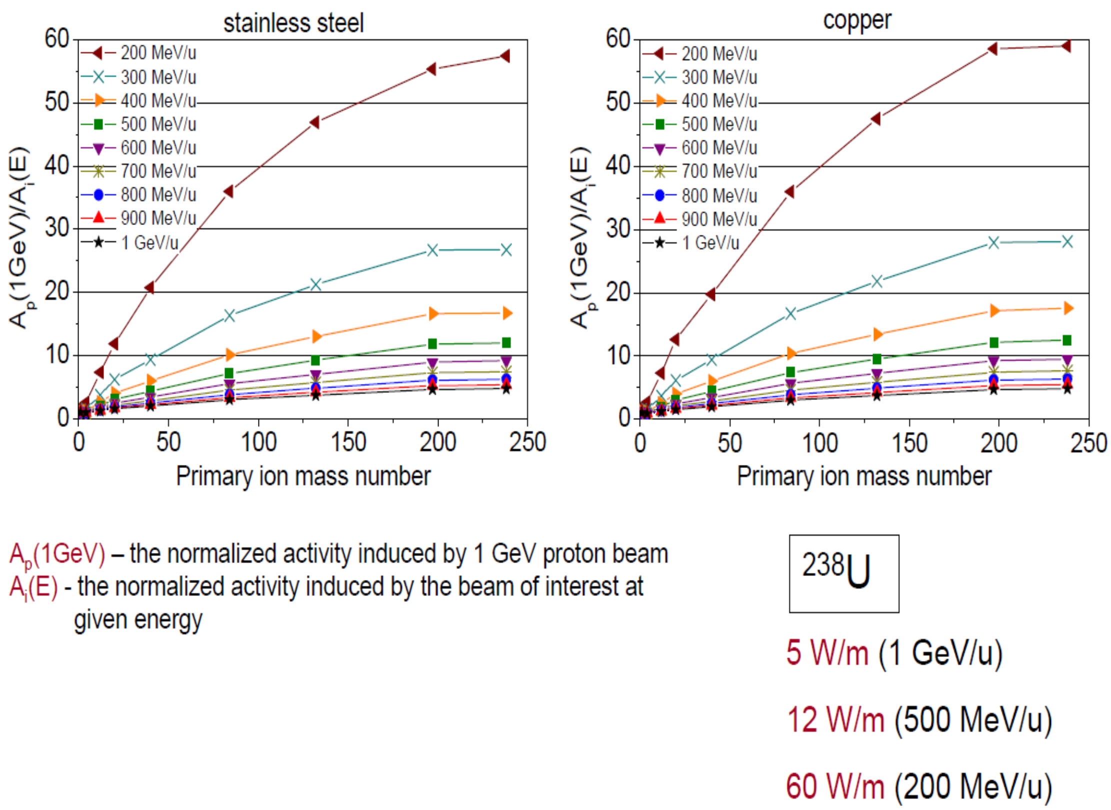

Figure 2: Activation results from the FAIR project. The activity is calculated per unit beam power, and normalized to a 1 GeV proton beam. See reference [10].

Working Group Presentations

Several short talks were presented in our working group. Highlights are presented below.

Robert Burke (Fusion Power Corporation), "Evolution of the Pulse Structure in the Single-Pass RF Driver"

Details of the pulse formats including telescoping of the multiple charge-state 1+ beams, progressive bunch and pulse combining, the differential acceleration scheme for a factor of 10 bunch compression, and final beam combining by telescoping at the target were presented for the Fusion Power Corporation Single-Pass RF Driver concept. The overall system layout was also presented. The expected transverse and longitudinal emittance budgets were discussed. The design concept is similar to HIDIF on the front end and eliminates the use of storage rings which were regarded as only marginally viable. Neutralized chamber transport is employed.

Rami Kishek (University of Maryland), "Space Charge Studies at Extreme Intensities in a Ring"

The experimental capabilities of the University of Maryland Electron Ring (UMER) were presented. UMER is a scaled experiment using high-current, low-energy electrons to better understand space charge dynamics at extreme intensities and can be used to study beam halos and mitigation techniques or phase-advance limits in FODO lattices with space charge over a wide range of parameters. This experimental capability should be used for beam halo proof-of-principle experiments related to HIF. Space-charge limit research may lead to simpler ring-based machine designs if more charge can be controlled in storage/compressor rings.

Yuri Batygin (LANL), "Self-Consistent Beam Current Limit in RF Accelerator"
An analytical solution for the self-consistent equilibrium particle distribution of a high-brightness beam in an RF accelerator was presented. Conditions for equipartitioning of the beam distribution and transverse and longitudinal current limits were obtained. A comparison of the analytical solution with an ellipsoidal bunched-beam model was also presented. This work can lead to better estimates for space-charge current limits of bunched beams.

Steve Lund (LLNL), "Comments on Space-Charge Limits in Linacs and Rings"
The optimization of linac and ring designs to operate at the space-charge limit was discussed. Typically both are designed to operate in the known region of stability for space-charge strength (tune depression) and applied focusing strength (phase advance) (See Fig. 3). It would be a "game changer" if rings in particular could be designed to operate at or beyond the conventional space-charge limits. This could lead to significant increases in transported ring current through a prescribed injection scheme that injects beam continuously at or beyond the current limit. An important outcome of this discussion is to revisit the concept of current limits and to explore if it is possible to exceed the Laslett tune-shift limits. Classical resonance conditions may not apply due to space-charge induced tune spread washing out resonances at high space charge due to phase mixing and Landau damping.

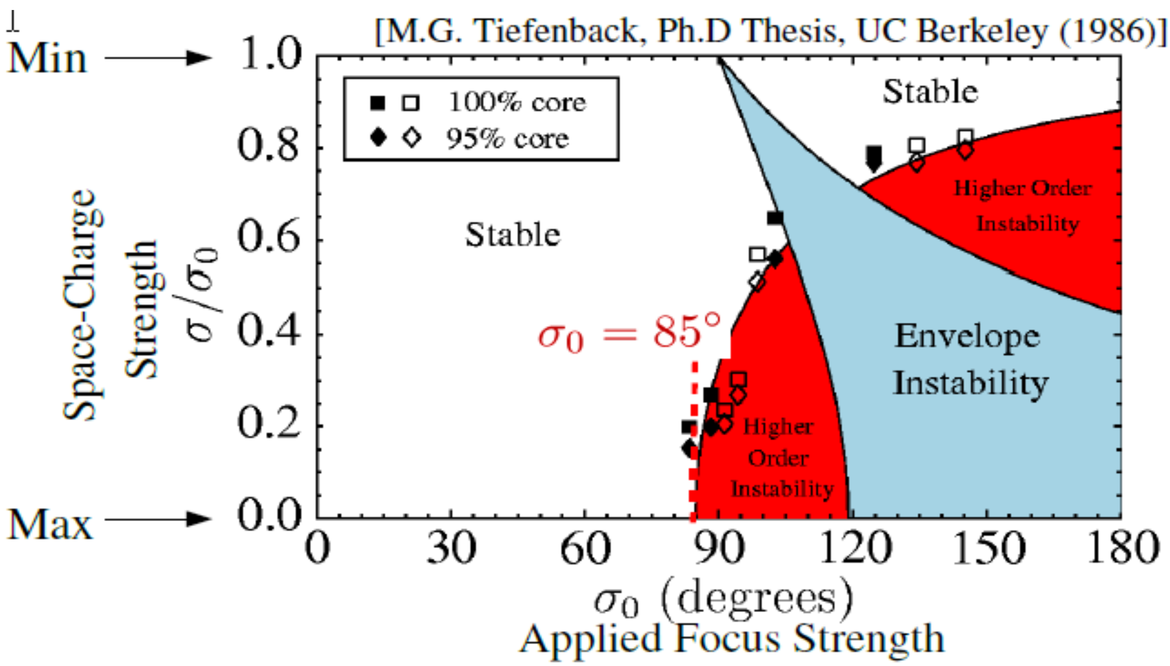

Figure 3: Tune depression vs. zero-current phase advance plot showing the region of stability in which most linacs and rings have been designed to operate.

John Staples (LBNL), "Comments on 2004 HEDP Workshop – RF WG Concept"
Design and preliminary simulation results of a 16-beam injector developed during the 2004 HEDP Workshop were discussed. Results were presented of a 1-μC, Ne^{+1} beam compressed to 1-ns pulse length, demonstrating that the de-bunched linac energy spread could be compressed a factor of 200. A beam current of 300 mA/beam was assumed (5 A total current, 200-ns pulse length) from each injector followed by a 50-MHz interdigital H-mode linac structure with multichannel solenoidal focusing.

Potential Design Concept – Extrapolating Existing Technology
A conservative example concept was discussed that addresses what is possible with modest extensions of existing technology at GSI/FAIR. This concept assumed a single-driver linac with three injectors

followed by a large storage ring and multiple smaller pulse-compression rings or a compressor induction linac. The large storage ring is required to damp out the ion source/injector current fluctuations that need to be < ±10% at the final focus. Accumulation time in the storage ring would be varied based on the injector output current. The basic system parameters are given below:

- U^{4+} Injector – 1-ms pulse, ~ 20 mA (need 1mC), MEVVA-like source (x 3 for reliability)
- 100-300 MeV/u linac – single beam, similar to upgraded UNILAC, ~1-km length
- Large Storage Ring – ~10 km circumference, 1-3x10^{14} ions achievable, need 10^{15} ions for 3 MJ, ~60-μs pulse, injection time determined by linac output, goal is to damp out ion source fluctuations.
- Pulse Compression – Smaller compression rings or induction linac (or other novel schemes)
- Transport/Final Focus – neutralized, ~100 m (TBD)

This approach is attractive since it is simple in comparison to the HIDIF design and takes advantage of existing technology. Possible use of induction bunching could allow an optimized hybrid design taking advantage of RF for high-gradient acceleration in the linac and induction bunching after (or in) the ring with flexible pulse compression capabilities if phase-space dilution can be limited in the rings. However, present MEVVA ion source performance is the weak point. A 1-Hz repetition rate has been demonstrated for this source but 5 Hz-10 Hz is needed. There are also source lifetime issues (may be mitigated by using multiple ion-source injectors). Presently it is unknown how to achieve the required 10^{15} ions for 3 MJ with this concept. Since this approach uses existing technology, most R&D effort would be focused on the final focus region to address space-charge issues. Increased space charge in the rings by minimizing beam storage/accumulation/bunching time and potentially related space-charge limits beyond conventional Laslett limits could further improve the concept.

Single-Pass RF Driver (Fusion Power Corporation)
A recently-developed concept for energy production was presented and discussed in significant detail. The Fusion Power Corporation Single-Pass RF Driver (SPRFD) concept is shown in Fig. 4. The concept assumes the use of readily available accelerator and ion-source/injector technologies and as such, is relatively conservative. Singly-charged ions are accelerated and combined progressively to deliver a 20-MJ compression pulse followed by 1-MJ ignition pulses to each end of cylindrical, direct-drive targets, in one of up to 20 chambers to increase economy of scale. The concept relies heavily on a set of novel beam manipulations (through appropriate beam merging and timing) that are conceived as a way to handle many different isotopes. It appears that sufficient redundancy exists to ensure a high level of plant availability, but a more detailed analysis, which was out of the scope of this workshop, is required to verify this conclusion.

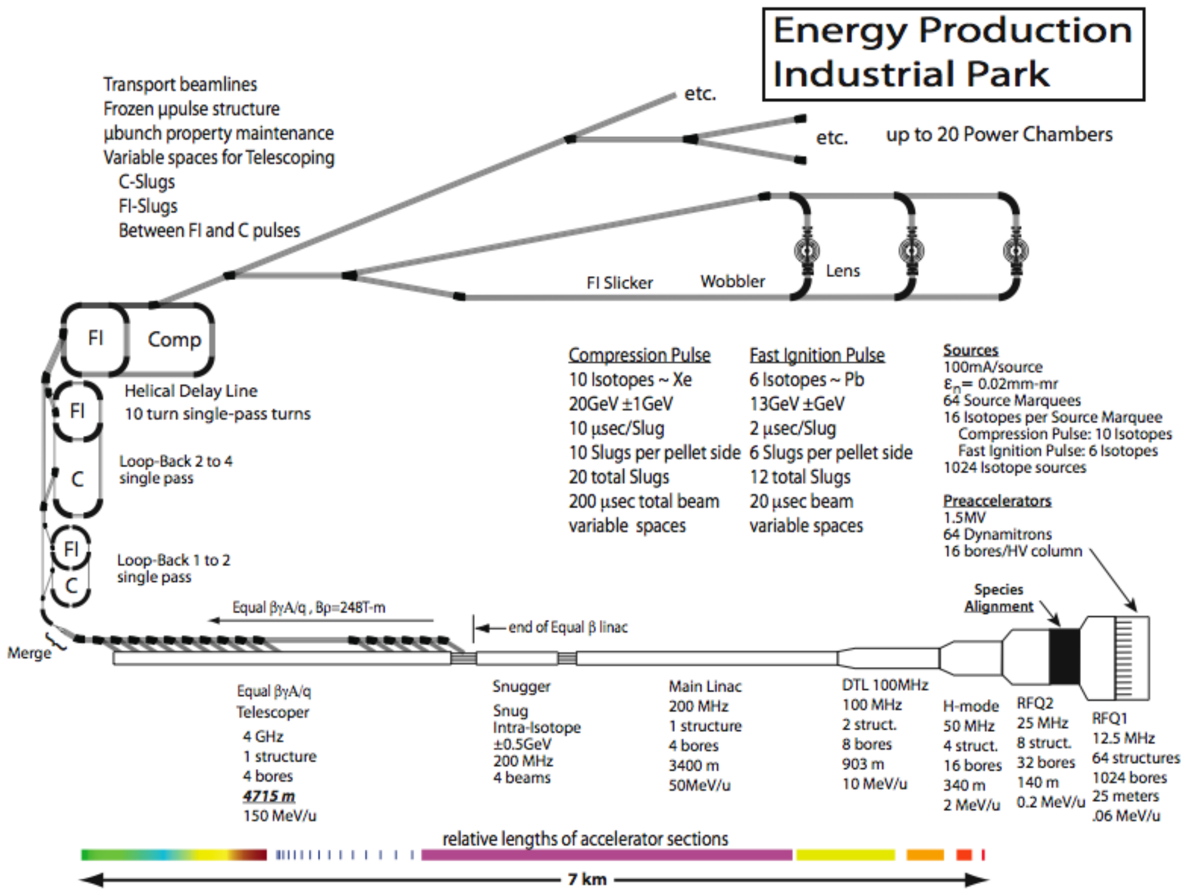

Figure 4: The Single-Pass RF Driver (SPRFD) concept.

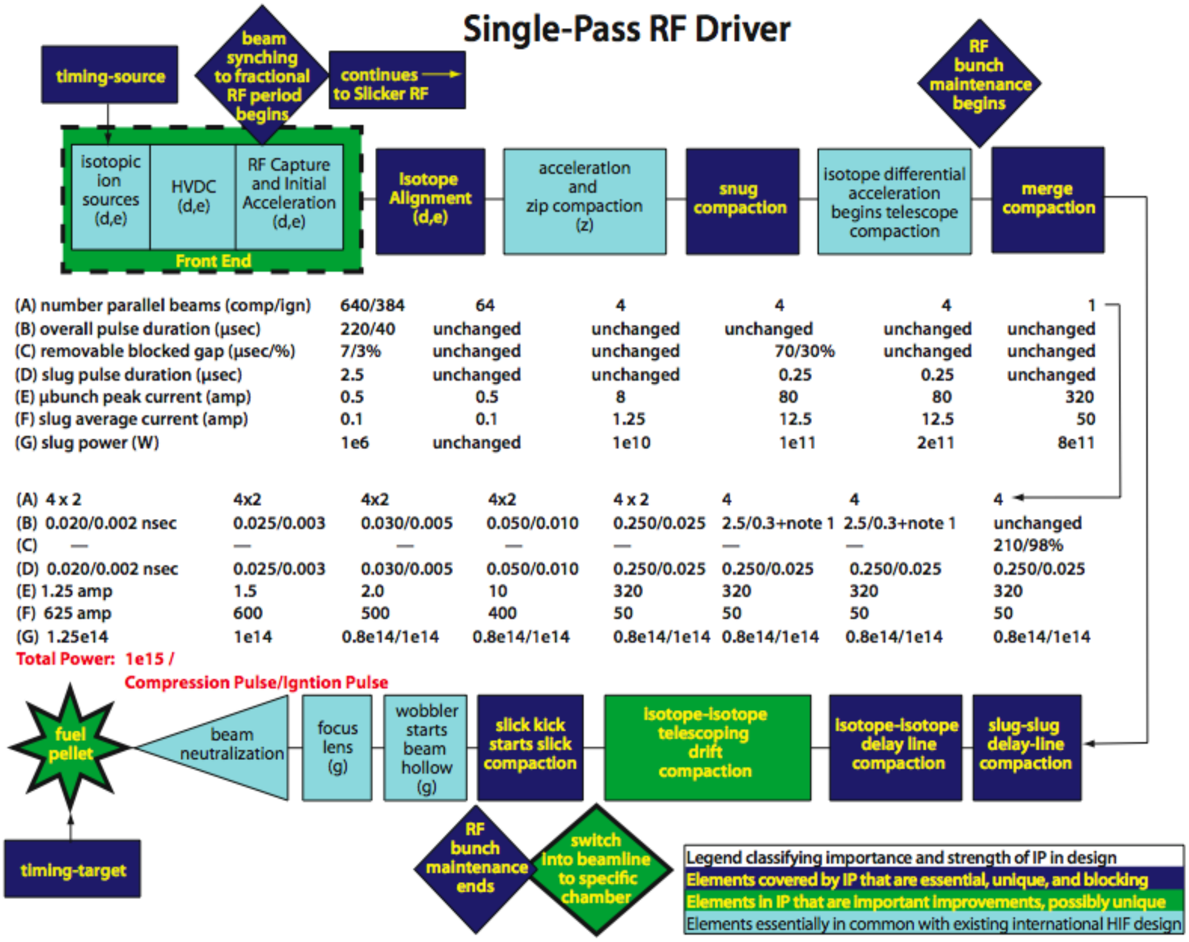

Figure 5: SPRFD subsystem details.

Much of the technical basis for this concept is grounded in the HIDIF design. However, there are several unique features including the elimination of the use of storage rings, the inclusion of the multiple target chambers, and details of beam manipulation and timing (see Fig. 5). The elimination of storage rings allows microbunch control which should preserve beam emittance and ease final focusing. The assumed 50-μm spot is estimated based on the HIDIF linac study, which included substantial growth of the emittance between the sources and the linac output.

While the concept appears to be well-developed and the proposed beam dynamics, under initial examination, are well within the experience of conventional RF accelerator systems, detailed beam dynamics simulations of either subsystems and/or an integrated end-to-end simulation would greatly enhance the technical footing of the design. This includes detailed simulations with errors. Such is common practice in accelerator system design today. Using available and well-benchmarked codes allows verification of otherwise estimated performance parameters such as emittance growth (and emittance budget), beam losses and activation, and the associated required control margins for RF, magnet, and other systems. The SPRFD concept assumes a factor of 3 emittance dilution during the beam manipulations between the linac and final focus. This will not be verifiable without substantial additional analysis.

There was significant discussion of the beam manipulations that are necessary to make the SPRFD concept work. Questions arose regarding what hardware systems would be used to perform some of these manipulations such as extracting beams of different species, merging, etc. It was not clear if these systems had been considered in detail. Technical gaps may exist and details of concept-to-implementation need to be addressed to place this concept on a firmer technical basis.

Potential Advantages of Eliminating Storage Rings

Elimination of storage rings to increase peak beam currents in an RF-based driver system in favor of a linac-only based system has the potential advantage of maintaining the microbunch structure of the beams. As a result, bunch-to-bunch space-charge interactions in the beam are negligible and minimal emittance growth is expected. The beam dynamics are dictated by the space charge of the microbunches, not the integrated charge of the pulse. Therefore, microbunch control and the subsequent preservation of the beam emittance will ease final focusing. It is recommended that a more careful analysis, supported by appropriate beam simulations, be carried out to verify these conclusions.

Pushing the Space-Charge Limits

Innovative methods should be sought to increase the driver output energy while assuming presently achievable parameters for ion source/injector beam currents. Existing simulation codes should be used to explore the potential to design and operate both linacs and rings at or beyond the typically assumed space-charge limits. Proof-of-principle experiments could also be carried out at existing facilities such as UMER.

Recent Advances

Several significant advances in accelerator technology and physics, beam transport, and HIF target design have been made in the last ten years or so that can improve the next generation of HIF driver designs. Higher-kinetic energy targets are being developed that would allow significant reductions in the required beam currents that the driver must deliver for the final compression and ignition energy. Progress has also been made in improving methods to neutralize the final beam transport to the target. This can relax the current limits of the driver beams due to space-charge effects. There have also been significant advances in understanding beam halo and electron-cloud effects, and ion lifetime issues. Being able to minimize or mitigate these effects enables designs with lower beam loss and resulting activation, and improves both driver and final focus performance.

Superconducting cavity technology (¼-wave/ ½-wave structures, IH/CH structures, spoke resonator cavities, elliptical cavities) has been applied to high-power proton linac designs (ORNL Spallation Neutron Source, accelerator production of tritium, accelerator-driven systems, etc.) and for heavy isotopes (University of Michigan FRIB). Use of this technology can reduce driver-accelerator footprints and significantly reduce overall power costs, both of which are important in realizing an efficient energy-production system. There is also promising new work in materials applied to superconducting accelerating structures that may lead to even higher average accelerating gradients in the near future.

Significant improvements in accelerator simulation codes [11] and computational capabilities over the last decade have enabled sophisticated high-current/high-brightness designs previously not envisioned. Use of these codes has led to an improved understanding of how to design high-power linacs that minimize beam halo and losses, allow for nearly current-independent transitions that improve operation and beam tuning, and are less sensitive to fault conditions. Most of these codes have been thoroughly benchmarked and should be used to develop and verify the next generation of driver designs. Advanced simulations are also essential to understanding the limits of neutralized beam transport in compression, final focusing, and chamber transport. Exploiting these tools can promise future design concepts with lower degrees of uncertainty in machine issues and performance.

Although not yet a standard practice in accelerator system design, Reliability, Availability, Maintainability, and Inspectability (RAMI) and Failure-Mode Effects Analysis (FMEA) models have been applied to understanding the overall plant performance of many operating accelerator facilities. These models and available world-wide data must be applied to the next generation of driver designs to help ensure the required high levels of reliability and availability needed (likely > 90%) for economical energy production.

Enabling R&D
Several areas of enabling R&D were recognized as needed to refine the next-generation driver requirements. These include:

- High-current, high-charge-state injectors /ion sources capable of pure species and low emittance.
- Final transport designs that are independent of driver topology. This enables easier driver system trade-off studies.
- Better integrated target and chamber designs.
- Several new enabling proof-of-principle experiments would be useful:
  UMER – transverse beam halo formation and mitigation; study of longitudinal bunch control for final compression.
  Beam transport space-charge neutralization experiments
  GSI /FAIR wobbler experiment
  Fusion Power Corp – multi-beam multi-isotope front-end, multi-beam multi-isotope manipulations
- Well benchmarked codes made available to evaluate concepts.
- New progress in intense beam diagnostics and beam control.

Technical Issues That Can Be Addressed
A clear path forward for HIF as a means of energy production needs to be defined. Past efforts in RF driver designs have not focused on developing viable systems for energy production, but rather on basic science R&D and as such, are not optimized for the energy application. We feel confident that a next-generation driver/target system can be developed for this purpose based on current RF accelerator technology and recent concepts. This includes exploiting recent RF and superconducting technology advances for HIF.

It is expected that all accelerator-based systems for energy production will be large power output (1 GWe or greater) systems. Large power output systems are common among the world's base-load energy suppliers. However, optimized fusion energy designs must be developed that minimize complexity to the extent possible to maximize operational reliability and performance. To do so will require extensive use of modern accelerator design and simulation codes and RAMI/FMEA data.

As target/chamber designs for energy production mature, it is expected that efficiency/gain trade-offs can be better understood. This will allow optimization of driver/target topologies including choices of appropriate accelerator technologies to maximize plant power efficiencies. Optimal driver architectures might contain aspects of both RF and induction designs. The average beam power for these systems is large (~ 20-200 MW). Accelerating structure RF source parameters can also be optimized for cost control.

Recommendations:

1. Now is the time for developing detailed conceptual designs for economical energy production that take advantage of decades of progress in accelerator physics and RF accelerator technology. An optimized design may be a combination of RF-accelerator and induction-linac technologies. A more detailed examination of the Single-Pass HIF Driver concept may be a good starting point.
2. National and international collaborations (including industry) should be encouraged to develop heavy-ion fusion energy.

3. Economy of scale issues should be studied. Conclusions could have significant impacts in defining the most viable approaches for energy production. Scale economies should increase profitability by lowering cost per kWh.
4. Development of improved high-charge state ion sources (q>1) is desirable. Higher output currents and higher brightness beams can immediately be leveraged to improve designs.
5. The beam physics of neutralization and space-charge limits should be better quantified. This will require continuing R&D efforts that include simulations and beam experiments. Efforts can be symbiotic with ongoing work in beam-driven WDM facilities such as the NDCX-II experiment at LBNL and GSI/FAIR.
6. An experimental program on heavy-ion physics including accumulation, compression, space-charge neutralization and beam-target interactions could be initiated using heavy-ion capabilities at Brookhaven National Laboratory.

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