Heavy Ion Fusion Pathway

B. Grant Logan

Director, U.S. Heavy Ion Fusion Science Virtual National Laboratory,
(HIFS-VNL) - collaboration of LBNL, LLNL, and PPPL heavy ion research

Fusion Power Associates
Annual Meeting

Washington DC

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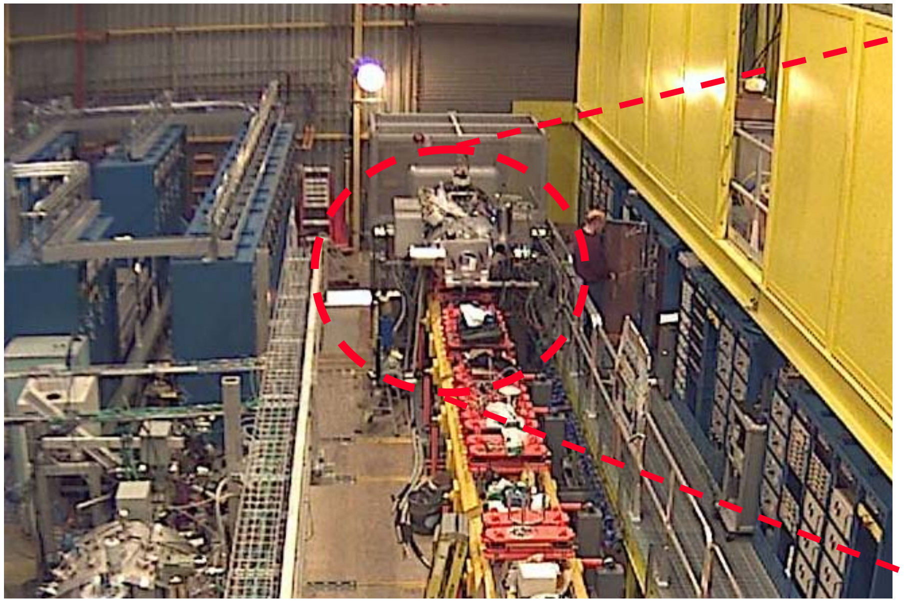
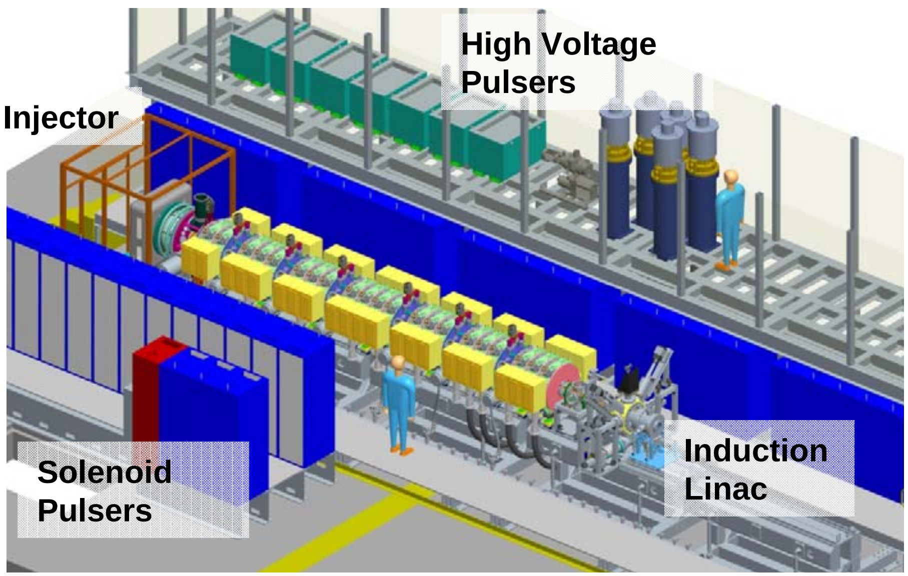
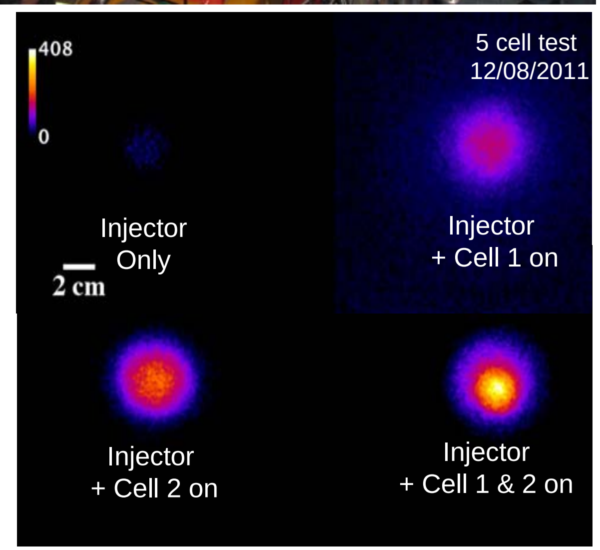
NDCX-II construction is nearing completion (ARRA March 2012). First beam tests (5-cells) meet minimum project acceptance goals.





<u>Schedule</u>:
with 10 cells to be installed by Jan 2012

With 27 cells to be installed by ~Mar 2012



The DOE Office of Science/ Fusion Energy Science includes driver-target coupling and advanced target physics *to enable heavy ion fusion*. *This program is part of inertial fusion energy science (IFES).*

U.S. DEPARTMENT OF ENERGY | Office of Science

HEDLP/IFES outlook, 5 years

(From Ed Synakowski to FESAC, March 2010)

- **National Ignition Facility (NIF) will have ignited**. FES will have a leadership role in developing IFES and astrophysical science experiments on NIF and on HEDLP facilities nationwide, in partnership with NNSA.
- FES, through its development of coordinated marches using the wide range of HEDLP facilities available, will be resolving fundamental questions of nature and pursuing science essential to assessing the viability of IFE. This range of scales can be levered in a scientifically sensible way
- For IFES, key questions to be pursued by FES include the multiscale physics challenges of advanced ignition concepts and the science of different drivers on the target
- Matter in Extreme Conditions Instrument (MECI) project at SLAC will be producing unique research on matter in extreme conditions relevant to fusion, planetary and astrophysical science, equations of state…
- National Drift Compression Experiment-II (NDCX-II) at LBNL will be assessing the issues surrounding the viability of heavy ion fusion.

The NAS study and NIF ignition campaign results will have a large impact on the specifics of what we ask FESAC.

TBD

Jan 29, 2011- We presented to NAS a requested R&D plan based on *presumed success of NIF*: three R&D phases to an HIF-IFE Demo:

PHASE I: 5 years x ~40 M$/yr: Integrated single beam accelerator experiments on NDCX-I and NDCX-II (extended with more cells), dynamic vacuum control experiments on HCX @ 5 Hz, scaled liquid chamber experiments, sub-ns planar shock experiments on NDCX-II, and HIF target design for indirect drive, direct drive shock, and X-target HIF options.

→***Deliverable:*** validation of heavy ion accelerator and implosion experiment design for Phase II, and for choice of target for Phase II.

PHASE II: Next 10 years x ~60-180 M$/yr: Heavy-Ion-Driven Implosion Experiment (HIDIX): a 10-kJ-scale, multiple beam accelerator prototype which drives first cryo D_2 target implosions and 5 Hz bursts of injected symcaps to learn precision pointing, balance, timing, etc. Includes supporting liquid chamber, target fabrication, and injection R&D for 5 Hz.

→***Deliverable:*** validation of approach to multi-beam accelerator and target for HIF ignition tests, using an accelerator designed for 5 Hz operation.

PHASE III: (>20 years) Construct 2-3 MJ HIF ignition test facility for single shot tests, then burst mode, using accelerator at 5 Hz. If successful, then add nuclear systems to upgrade to 150 MW ave. fusion power level HIF-IFE DEMO.

→Its not premature to consider a "Plan B" that allows more time to assess NIF results and to make progress with more modest near-term budgets.

Phase I: Next five year goals (more affordable plan B strawman)

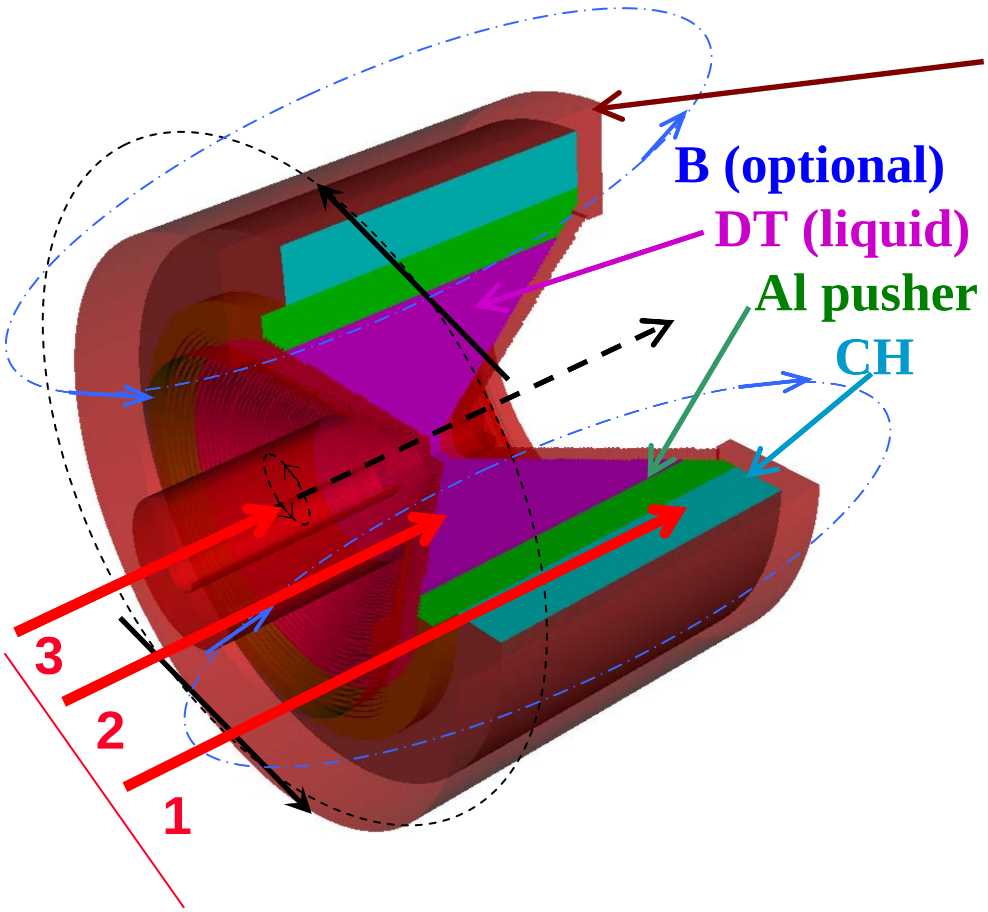
→**Strategy:** focus limited effort on selected HEDLP topics that are common to both recommended HEDP science as well as enabling heavy ion fusion targets.

→**HEDLP:** the 2009 Fusion Energy Science Advisory Committee (R. Betti) report "Advancing the Science of High Energy Density Laboratory Plasmas" emphasized science needs in areas relevant to heavy ion fusion; (1) *HED Hydrodynamics (including advanced, high gain targets), (2) Intense Beam Physics, (3) Magnetized HED plasmas, and (4)Warm Dense Matter.*

→**5 year goal:** Utilize NDCX-II and develop joint collaborations between the US HIFS-VNL and GSI-FAIR (present MOA to be updated), and with other willing partners, e.g., LANL's LANSCE-PSR (MOA draft working up LANL management), to leverage use of existing facilities and to make more rapid scientific progress through shared diagnostics and modeling.

→**Plan B Budget requirement:** modest growth of HIFS-VNL budget from present 7.7 M$/yr to ~16M$/yr, including support for joint collaborations.

X-target discovery: single-sided beam illumination *along z-axis* can compress fuel *quasi-spherically in radius* to rho-r > 2 g/cm^2 for high gain!



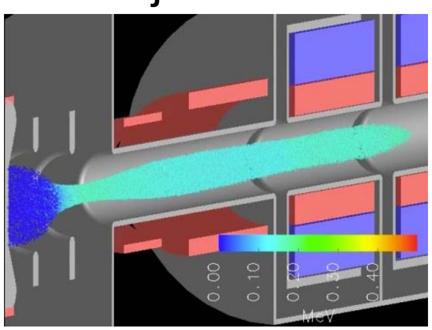
- •Lowest convergence (~5) of fuel required for any 2-D high gain IFE target→ maybe more robust to hydro instabilities and mix ←key!
- •Highest gain (> 200) and yield (> 1GJ) for any HIF target in 2D design →enables simple gravity-cleared liquid chambers at low pulse rates ~ 1 Hz
- •Highest range accepted for ions→ lowest beam currents in accelerator
- •Single sided beam illumination with < 10 degree envelope half-angle for final focus array→ simplifies driver-chamber interface and beam manipulations
- •Simple low precision metal case with liquid DT fill → easy fabrication tolerances and low cost

Challenge: how can the **HIF program get <u>experimental data</u> related to X-target physics over the next 10 years?**

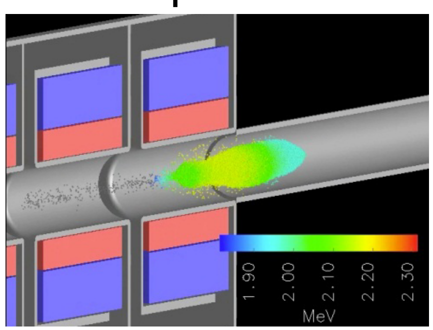
NDCX-II can explore more intense beam compression to sub-ns pulses relevant to shocks and HIF target physics

- 11 M$ construction began July 2009, to be completed in March of 2012 (ARRA project)
- Rapid initial bunch compression allows re-use of 70-ns pulsed power sources from the ATA accelerator, and compressed to sub-ns.
- Detailed 3-D simulations using the Warp code confirmed the physics design & set engineering requirements
- rapid initial bunch compression could reduce front end length and cost for HIF drivers

During injection



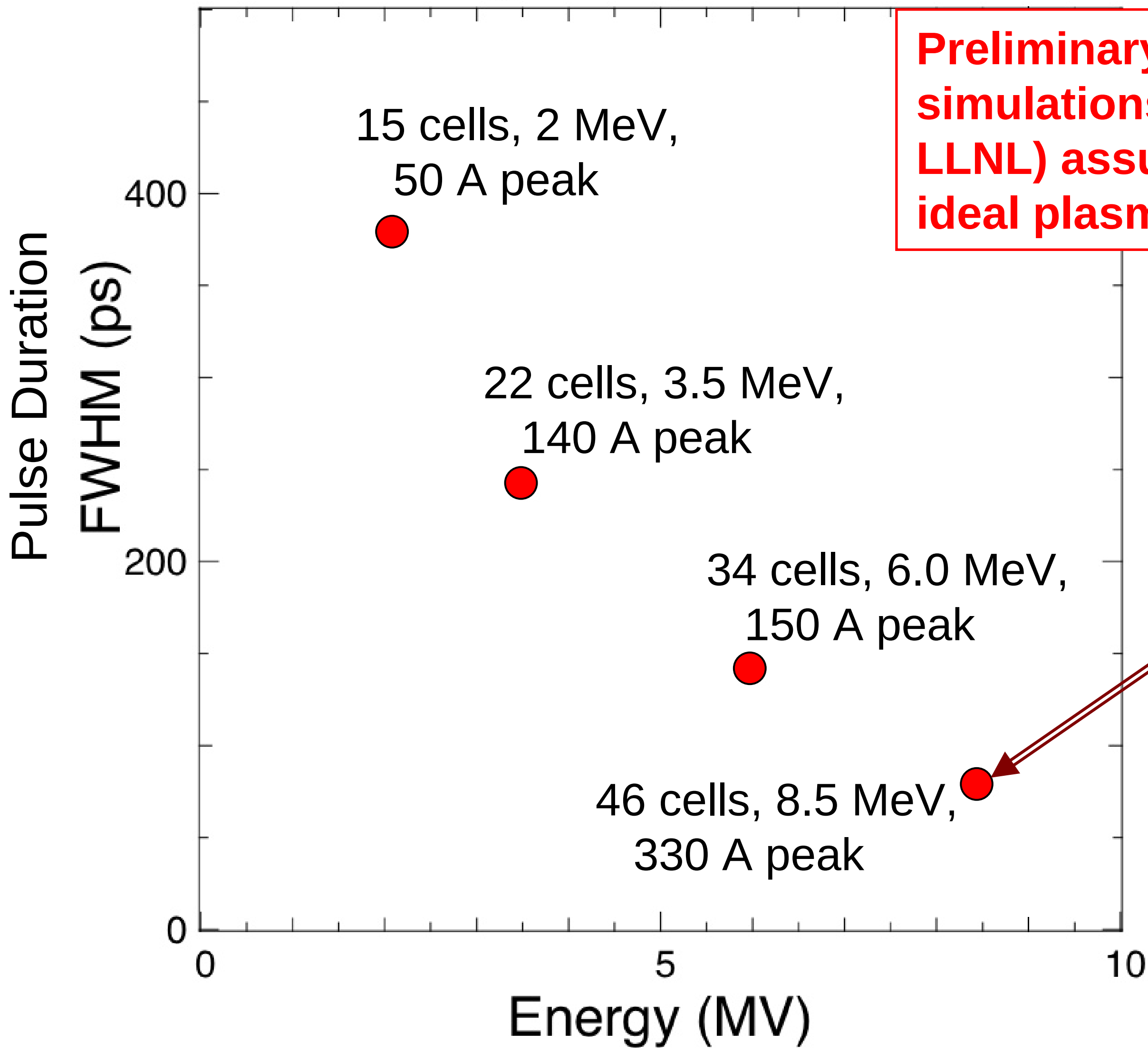
Entering final compression



Ref: A. Friedman, et al., *Phys Plasmas*, 2010)

	NDCX-I	NDCX-II (baseline)
Ion species	K^+ (A=39)	Li^+ (A=7)
Ion energy	300-400 keV	(1.2 MeV) → > 4 MeV
Focal radius	1.5 - 3 mm	(0.5 mm)
Pulse duration	2 - 4 ns	~(1 ns) → < 200ps
Peak current	~ 2 A	~ (10 A) → > 100 A

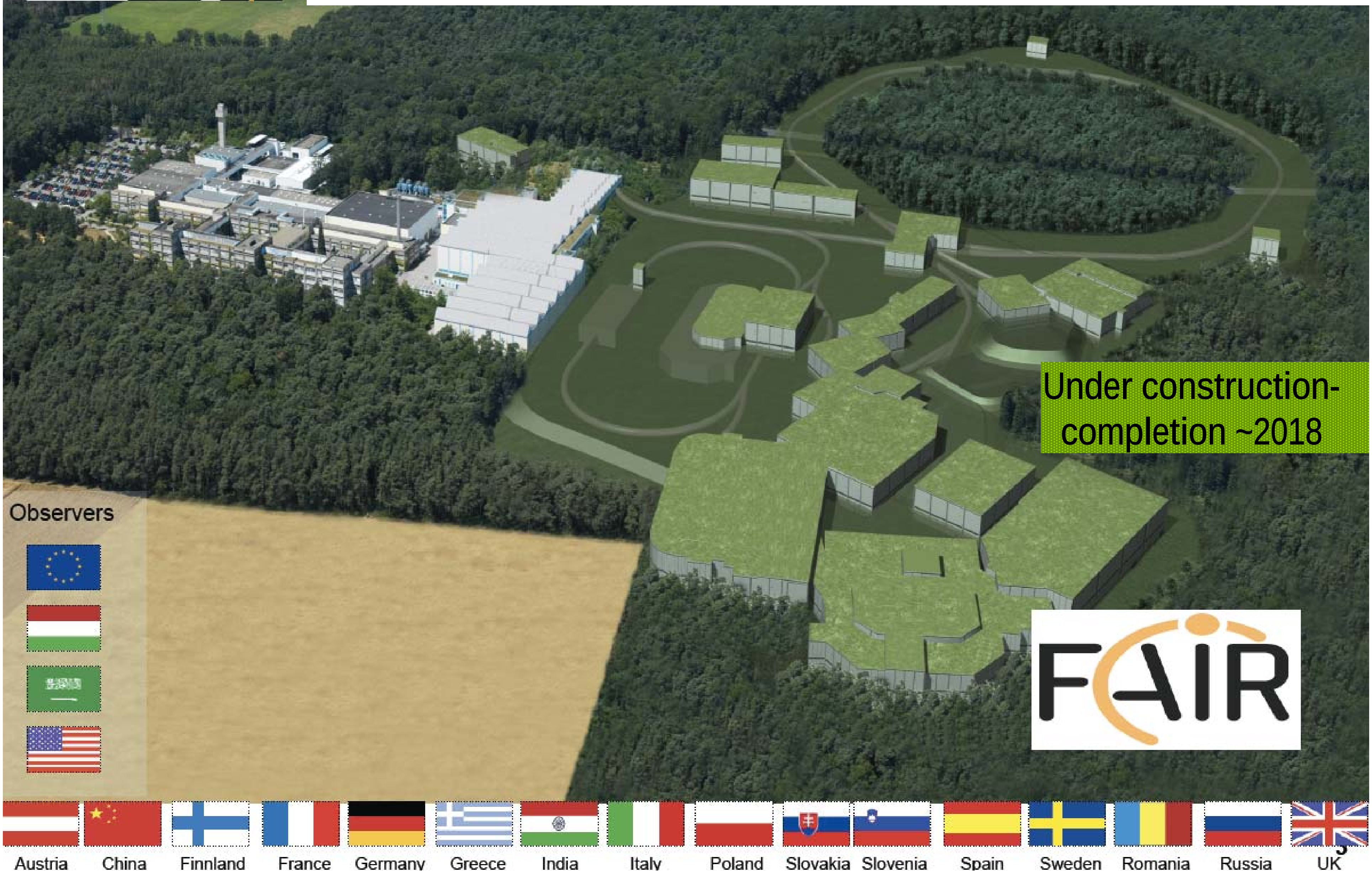
Simulations show potential of NDCX-II to compress pulses to a few hundred ps, motivating experiments related to shock or fast ignition



Preliminary results of Warp PIC simulations (Friedman, Grote LLNL) assuming jitter errors with ideal plasma neutralization.

We have 50 ATA cells to use, and could be added in < 2 years!

Last month (Oct.31) FAIR Scientific Director Boris Sharkov was invited by the US NAS panel meeting in Washington DC *to present research in Europe and Russia related to* Heavy Ion Fusion.



Scientific Director Sharkov appealed to the NAS for US to consider FAIR

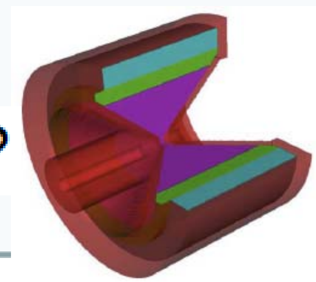
FAIR

Facility for Antiproton and Ions Research

– the light tower of the ESFRI Roadmap

Austria China Finland France Germany Greece India Italy Poland Romania Russia Slovakia Slovenia Spain Sweden U K Saudi Arabia

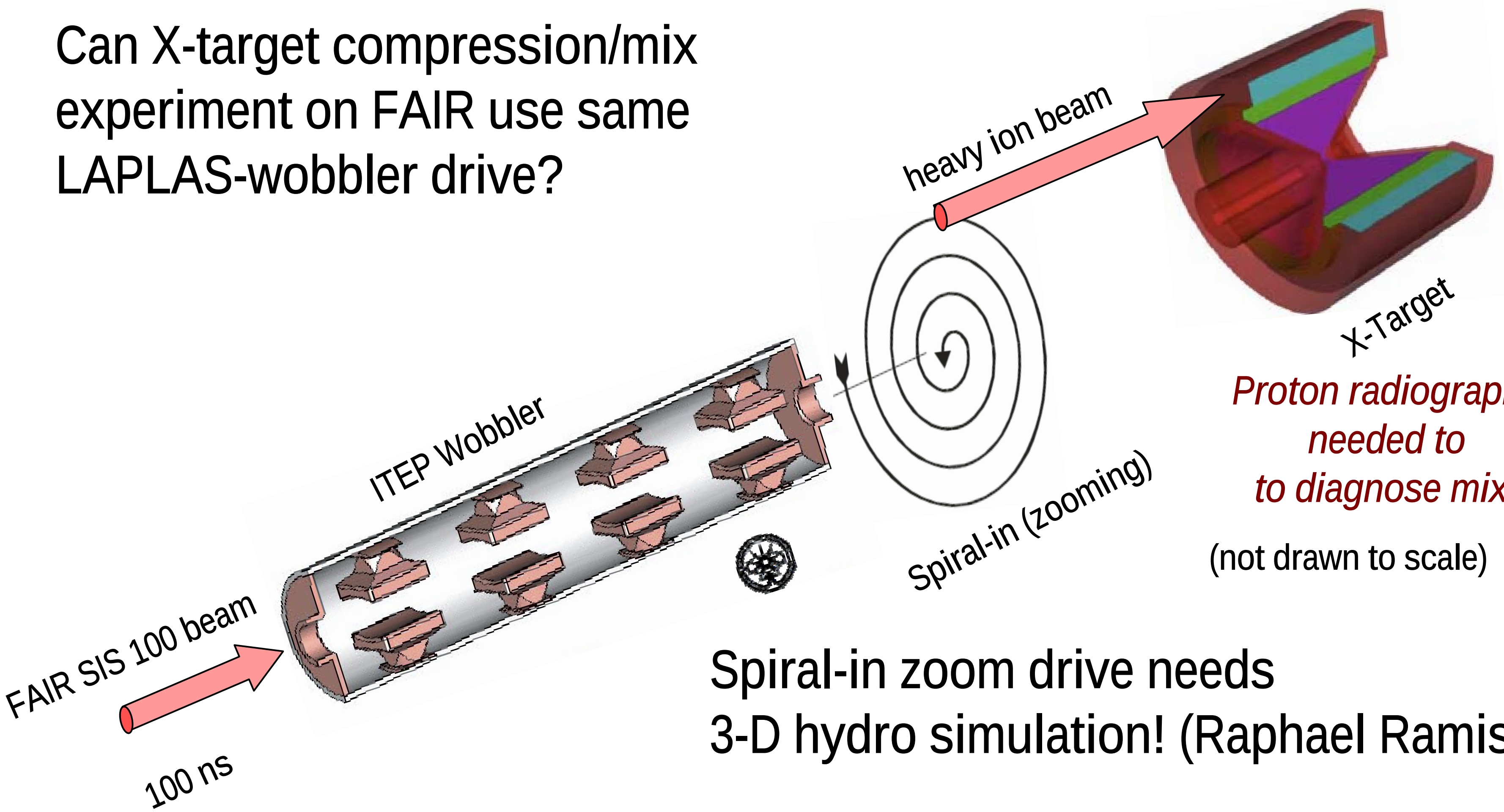
Become FAIR enthusiasts –

X-Target @ FAIR ?  **join FAIR !**

Sharkov suggested as little as a few M/yr* could support US as a FAIR user.
*plus contributions in kind provided by US domestic R&D

Topic 1: HED Hydrodynamics. Idea below is expressed by juxtaposing clips extracted from 3 slides of Prof. Dr. Sharkov's presentation to the US National Academy October 31, 2011:

Can X-target compression/mix experiment on FAIR use same LAPLAS-wobbler drive?



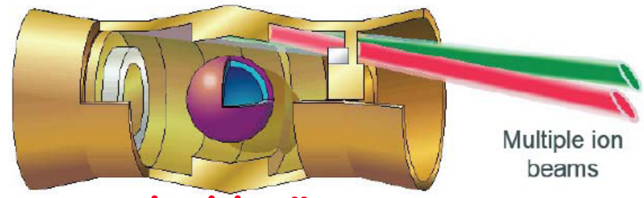
Proton radiography needed to to diagnose mix!

(not drawn to scale)

Spiral-in zoom drive needs 3-D hydro simulation! (Raphael Ramis)

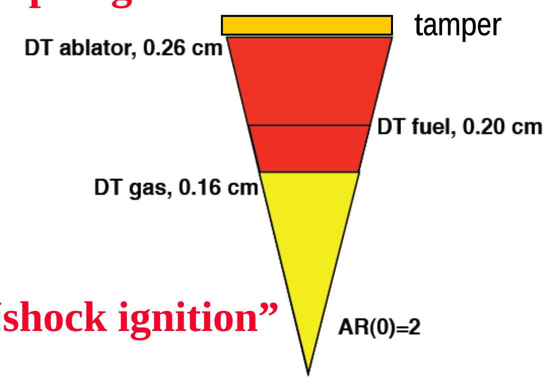
There are three basic classes of heavy ion fusion target options. No downselection is planned until NIF data is completed and assessed.

- **<u>Indirect drive</u>** <u>(2-sided hohlraum)</u> *2-D Lasnex design (2002):* 7 MJ, 3& 4 GeV Bi^{+1} , gain 68. <u>Two-sided illumination, like NIF</u>.



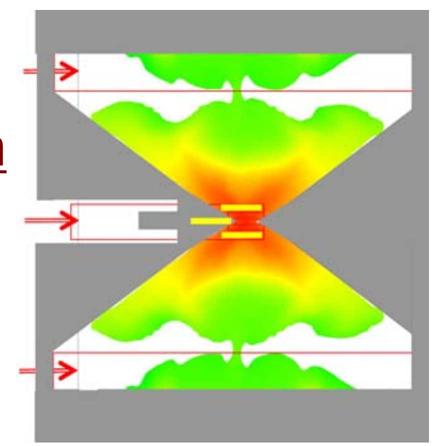
"hot-spot ignition"

- **<u>Polar direct drive</u>** *1-D Lasnex design (2010):* 3 MJ, 3 GeV, Hg^{+1} ion beams, gain ~150. Future 2-D design planned for polar drive illumination, <u>with tamper & shock ignition assist</u>.



"shock ignition"

- **<u>X-target</u>** <u>single-sided direct-drive</u> *2-D Hydra design(2011)* [Henestroza, Logan & Perkins, Phys. of Plasmas 18 (2011)] Gain 50 @ 6 MJ, range ~1 g/cm² ions. <u>Now, with an aluminum pusher→ **gain> 400** with 3 MJ of 2 g/cm² range ions.</u>


"fast ignition"

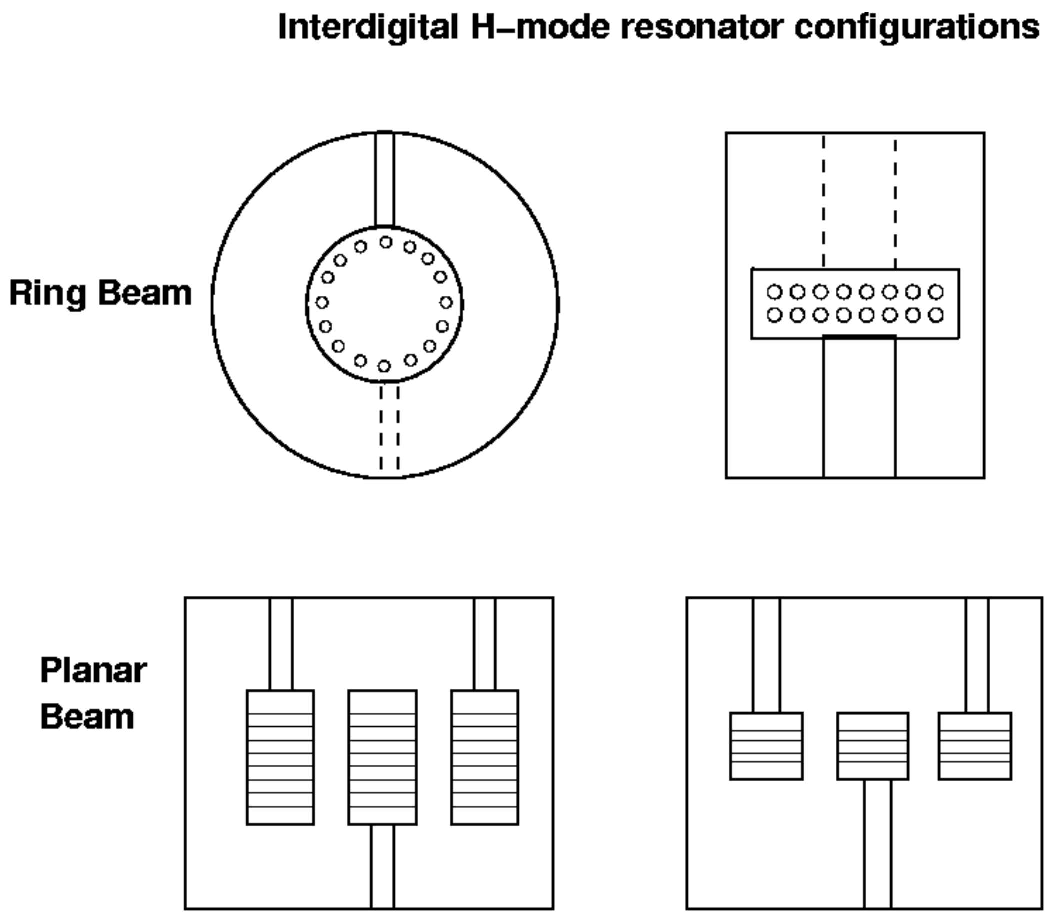
→All three options are intended to use multiple-beam linac drivers with thick-liquid-protected chambers to mitigate material neutron damage risks.

The X-target accepts ions with range 70 times higher than for either indirect drive or direct drive (hot-spot ignition) targets
→ *enough to reconsider candidacy of RF accelerators as heavy ion drivers*
→ *can tap predominant RF accelerator expertise of the world*

Example of a high current front end HI-RF linac design from previous 2004 heavy ion accelerator workshop for HEDP

The RF Linac Group

John Staples, Andy Sessler, Joe Kwan, Rod Keller, LBNL
Paul Schlossow, Tech-X
Peter Ostroumov, ANL
Wieren Chou, FNAL
Bill Herrmannsfeldt, SLAC



Conclusions:

- We presented a three phase plan for development of heavy ion fusion to the NAS in January, with budget requirements and decision criteria, that presumed ignition in NIF.
- Target physics affects target designs that set requirements for heavy ion accelerator drivers.
- We are developing a more modest Plan B to allow more time to assess NIF results, optimize heavy ion target designs, and to make progress possible under more constrained budgets.
- NDCX-II can address many key beam-target coupling physics over the next 5 years with 0.1 J sub-ns ion pulses.
- Over the next 10 years, we have opportunity to consider kJ-scale heavy ion beam target experiments using the FAIR facility now under construction at GSI.