HEDP and Heavy Ion Fusion

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&
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Session on *The DOE Program in High Energy Density Physics*

summary

(1) a range of science using NDCX-II
(2) a renewed Heavy Ion Fusion (HIF) program

- Neutralized Drift Compression Experiment (NDCX-II) enables studies of warm dense matter (WDM), materials science, and heavy-ion fusion.
  - NDCX-II operational status
  - Presently used to explore defect dynamics in solids
  - Complementing other HEDP research: Uniform heating of matter.
- HIF remains an attractive approach to IFE.
- The NRC report endorses HIF as a promising IFE approach and outlines elements of a balanced IFE program.
- A renewed HIF / IFE program should include innovative research from source to target.

We are hopeful that a seed Heavy Ion Fusion program will be restored. This would preserve the knowledge and capabilities built up by the Heavy Ion Fusion Virtual National Laboratory and its collaborators in anticipation of a future program in IFE.

NDCX-II is a facility designed to study both intense beam compression and Warm Dense Matter (WDM)

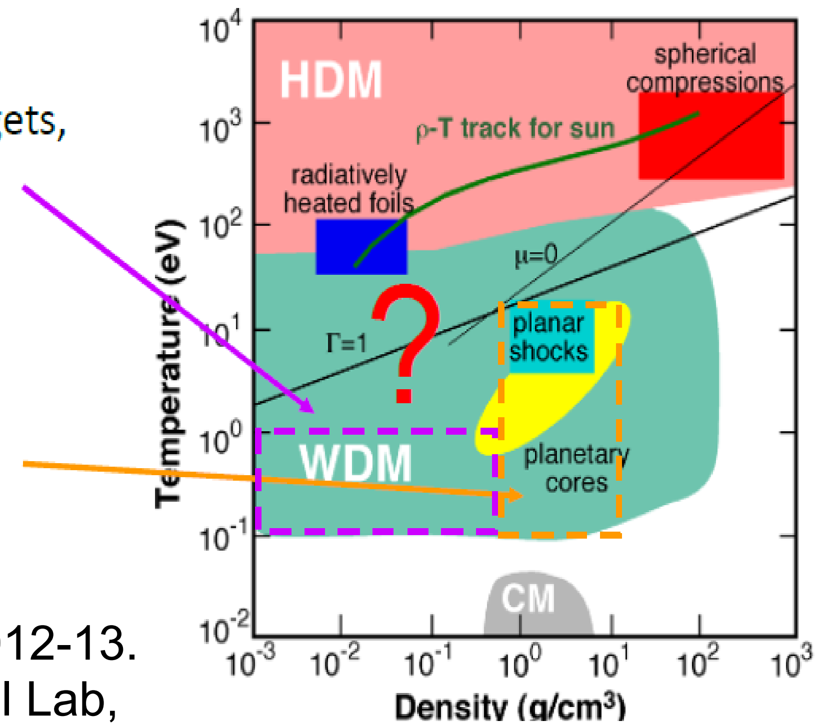
A scientific question for heavy ion beams identified in the National HEDP Task Force Report and in the April 2005 FESAC Fusion Priorities Report:
How can heavy ion beams be compressed to the high intensities required for creating high energy density matter and fusion ignition condition?

STAGE-I (Long pulse, 0.9 ns, 13 J/cm2)

- EOS of matter at under-solid density (foam targets, cryo target) ←long pulse implies expansion to densities below solid density

STAGE-II (Short pulse, 0.2 ns, 22 J/cm2)

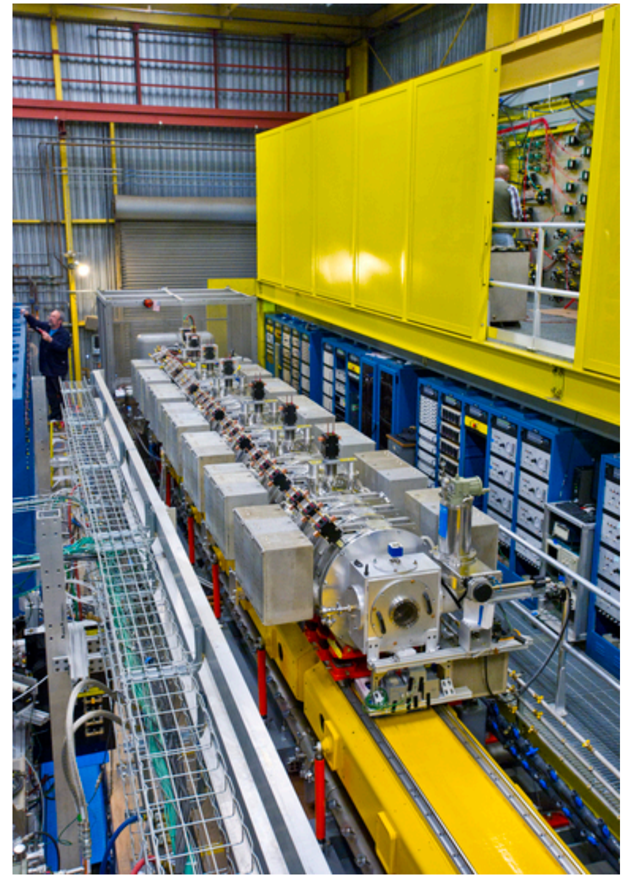
- Isochoric heating→ EOS of solid density matter
- Ion beam driven shock waves.
- Hydro instabilities studies .



Constructed 2009-12, commissioning in 2012-13. Heavy Ion Fusion Sciences Virtual National Lab, LBNL, LLNL, PPPL

NDCX-II: Constructed 2009-12, commissioning and first experiments 2012-13

	Now	With modest investment
Ion species	Li^+ (A=7) (also K^+, in preparation)	
Total charge / pulse (nC) # ions / pulse	30 , $2x10^{11}$	50 $3x10^{11}$
Ion kinetic energy (MeV)	0.3	1.2, 3
Focal radius (50% of beam)	~10 mm	0.6 mm
Pulse duration (FWHM, ns)	20 - ~600	0.6 - ~600
Peak current (A)	0.8	38
Peak fluence (time integrated)	~10 m J/cm^2	5-10 J/cm^2
Dose rate ($ions/cm^2/s$)	~10^{18}	~$5x10^{22}$



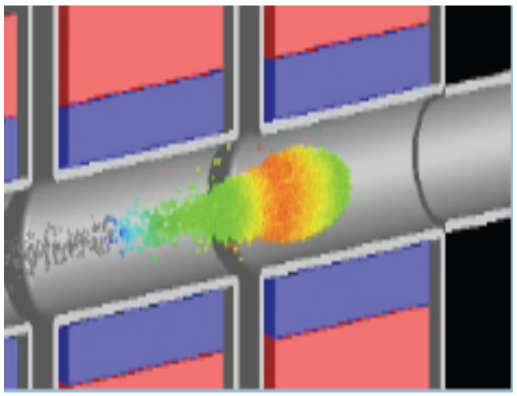
Control dose rate over six orders of magnitude through control of charge/pulse, pulse length and spot size.

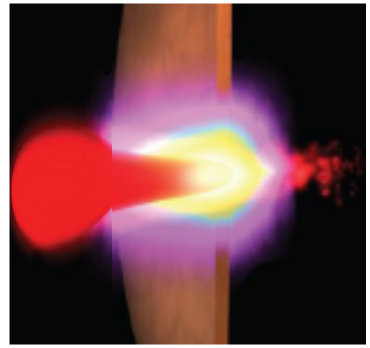
7 refereed papers on accelerator design and science possible with NDCX-II in Proc. 19th Int'l. Symp. on Heavy Ion Inertial Fusion, NIM A V733 (2013).

There is no FES support for NDCX-II or heavy ion fusion research since 2012.

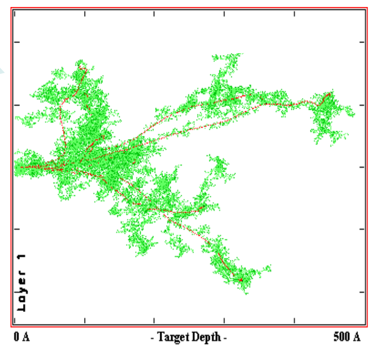
Pump-Probe experiments with ion beams give us access to defect dynamics in solids

Sub-ns ion beam pulses ("pump")





<u>High intensity</u>: Warm Dense Matter



<u>Lower intensity</u>: defect dynamics in materials. **These experiments on NDCX-II are presently supported by an internal LBNL LDRD (T. Schenkel, PI).**

•1 to 30 nC (~10^{10} to 10^{11} ions), 0.3 MeV, 10 mm^2, 20 ns

isolated cascades → overlapping cascades → amorphization and melting → warm (>1 eV), dense matter

50 nC, 1-3 MeV Li^+, 1 mm^2, 1 ns

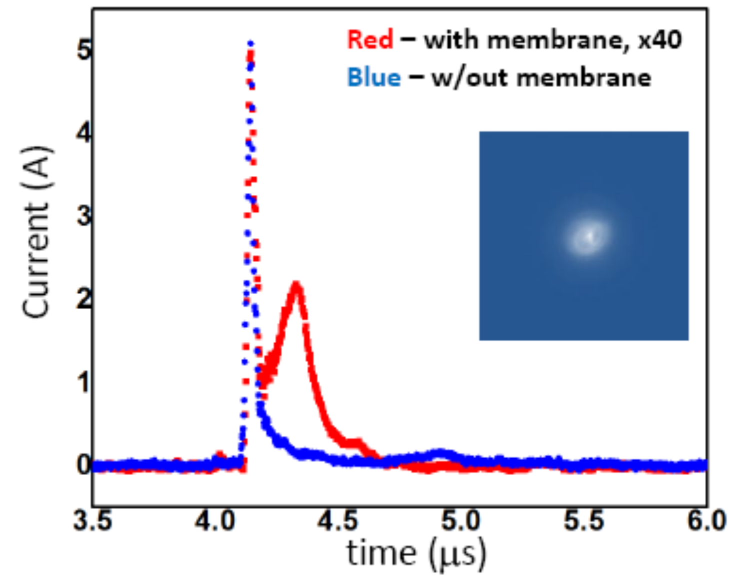
We will seek leveraged support from BES, HEP, NE, where there is an overlapping scientific mission.

Exploring multi-scale dynamics of materials far from equilibrium with pulsed ion beams at NDCX-II

	Now	With modest investment
Ion kinetic energy (MeV)	0.23 - 0.3	1.2 - 3
Beam spot (mm^2)	5 to 10	1
Pulse length (ns)	15 to 600	0.6 to 600
Time resolved diagnostics	Ion channeling	Electron beam diffraction

With support, NDCX-II could:

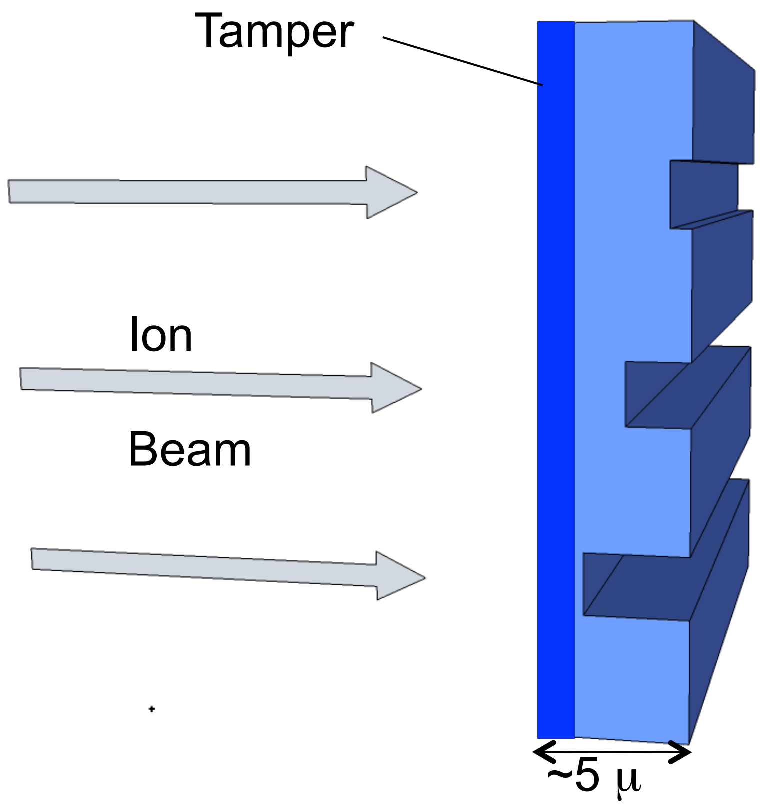
- **deliver materials physics results on defect evolution** from sub-ps to seconds for a range of excitation regimes from isolated collision cascades to melting and warm dense matter.
- Data will **benchmark simulation codes,** which currently "fly blind", with no connection to data on short time scales.
- Gain fundamental **understanding of damage evolution in natural radiation processes, inform materials and process development for applications** (e. g. detectors, nuclear, bio-rad, …)
- Complementary to ion pulses from laser-plasma acceleration, NDCX-II delivers highly **reproducible, tunable ion beams**



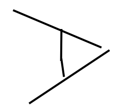
Time resolved detection of lithium ion transmission through a silicon membrane (red) reveals lattice damage built up during the 40 ns pulse, causing de-channeling of ions and profile broadening as compared to the pulse profile without the membrane (blue).

T. Schenkel, et al., Nucl. Instr. Meth. B 315, 350, (2013).

Possible target coupling experiments with NDCX-II: Conductivity in heated matter, Ion-beam stopping in heated material; Hydrodynamic experiments on volumetrically heated targets



Eg: Thermal conductivity can be measured by determining time for heat to reach various depths in foils thicker than range of ions

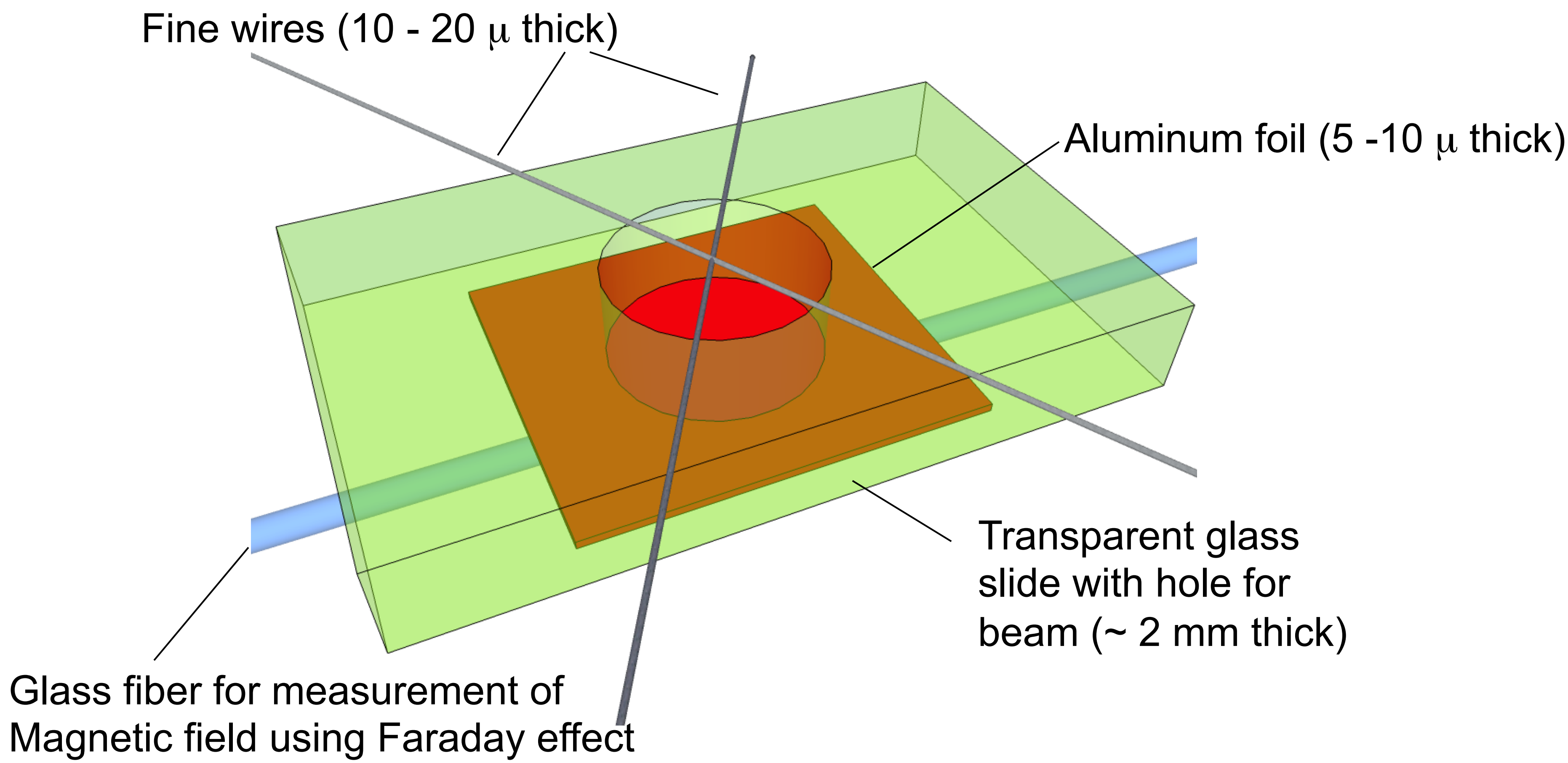


This experiment will be carried out at low ion intensities, so that the material is below the vaporization temperature

Schematic for "stepped target" conductivity measurements. **Ion beam heats tamper and rest of target nearly uniformly.** Thermal wave from higher temperature tamped region 'breaks out" at times depending on depth of grooves and heated material conductivity.

These are examples from 5 proposals submitted to DOE.

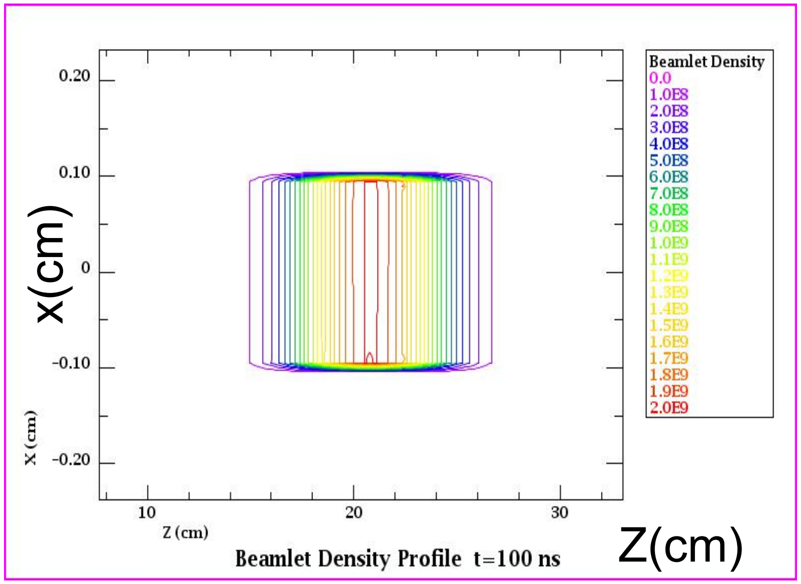
… Conductivity of heated material may be determined using measurement of magnetic diffusion time

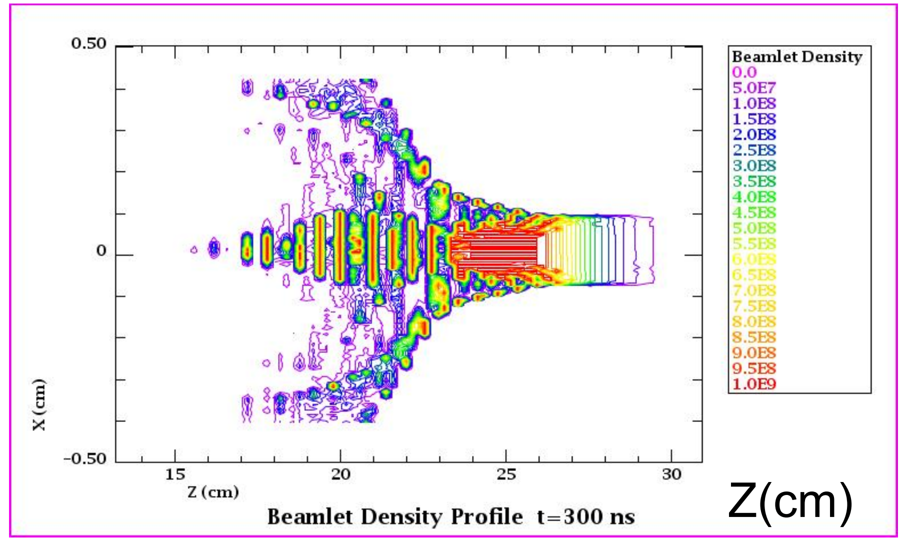


A voltage is rapidly pulsed across the fine wires. Ion beam heats foil and magnetic field diffuses through foil, depending on resistivity of heated foil. Magnetic field is measured using Faraday effect through the optical fiber.

Physics of intense beams: We can explore the transverse defocusing of the beam due to the two-stream instability.

E. Tokluoglu (PPPL), et al (2013)





Beamlet Density Contour at t = 100 ns (1 m of propagation).

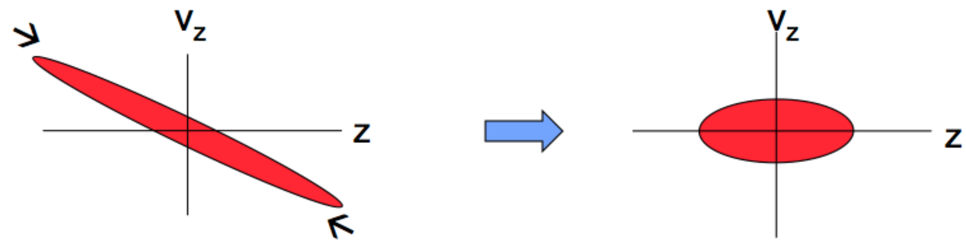
Beam Density Contour at t = 300 ns (3 m of propagation).

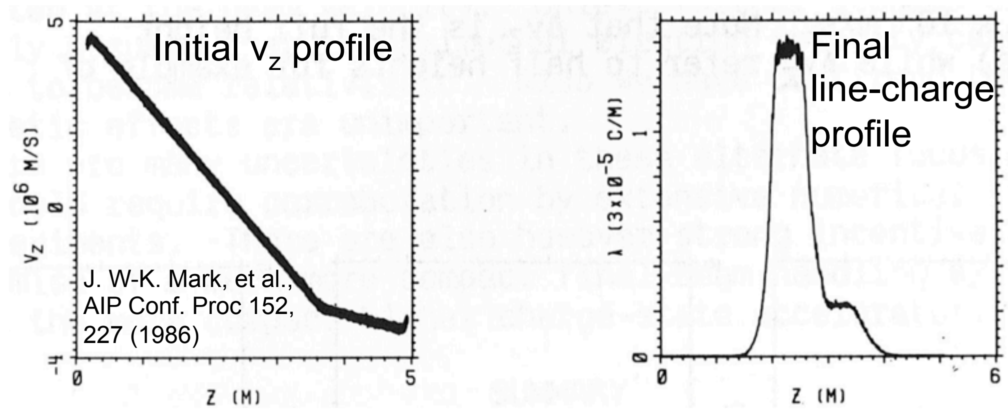
NDCX-II beam parameters for apertured beam r_b=1 mm. $\Delta v/v$ small,
…*but the defocusing effect is absent with a velocity spread ≈ few %.*

HIF-relevant beam experiments on NDCX-II can study

- How well can space charge "stagnate" the compression to produce a "mono-energetic" beam at the final focus?

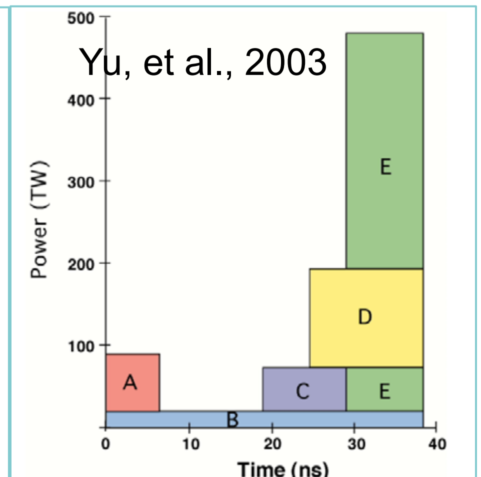
- How well can we pulse-shape a beam during drift compression
(vs. "building blocks")?





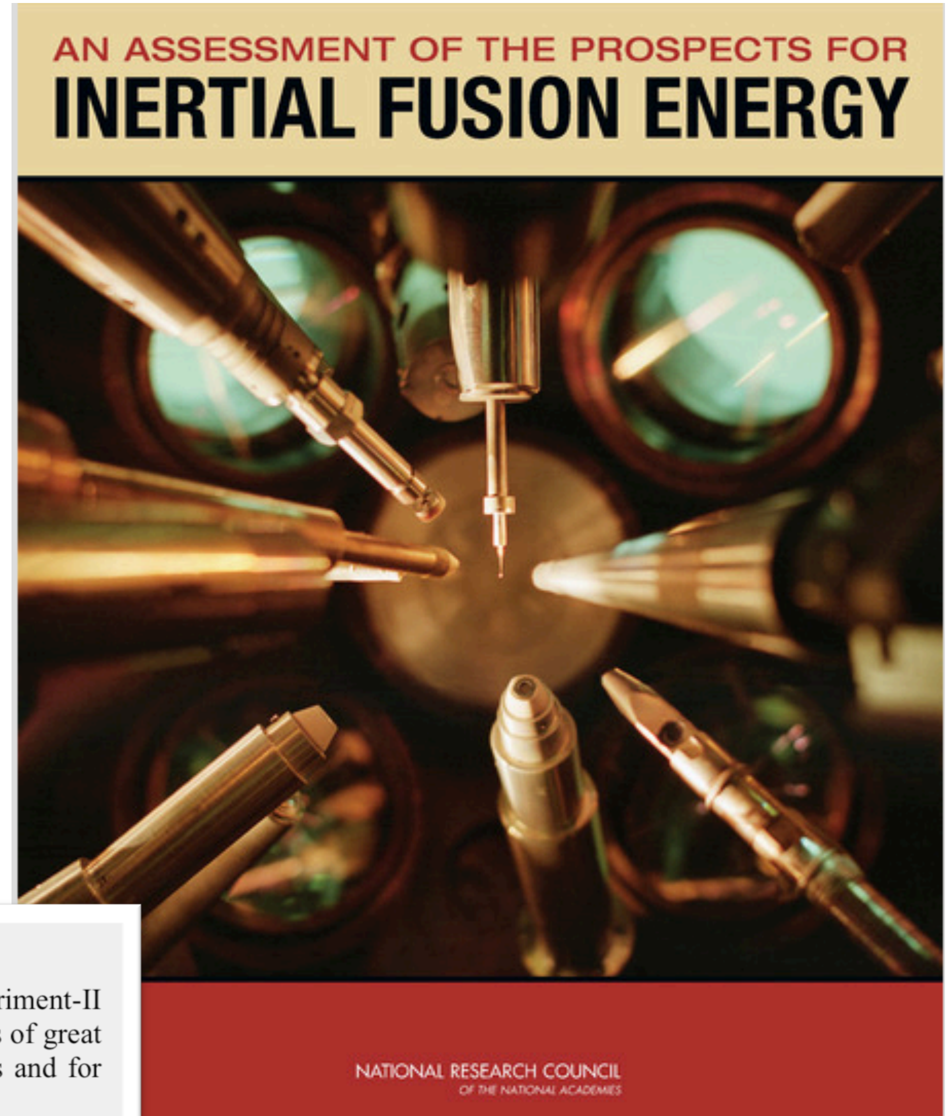
Dimensionless parameters (perveance, "tune depression," compression ratio) will be similar to those in a driver.

Pulse shape delivered to the fusion target comprised of five separate blocks with different powers and durations.



Heavy ion driven inertial fusion energy research

- NRC report (2013) is optimistic about NIF, and supportive of the HIF approach to IFE.
- Other issues:
  - DOE FES is waiting for NIF ignition
  - US commitment to ITER
  - Presently no support for Heavy Ion Fusion in OFES.
  - Major repercussions for future IFE research.

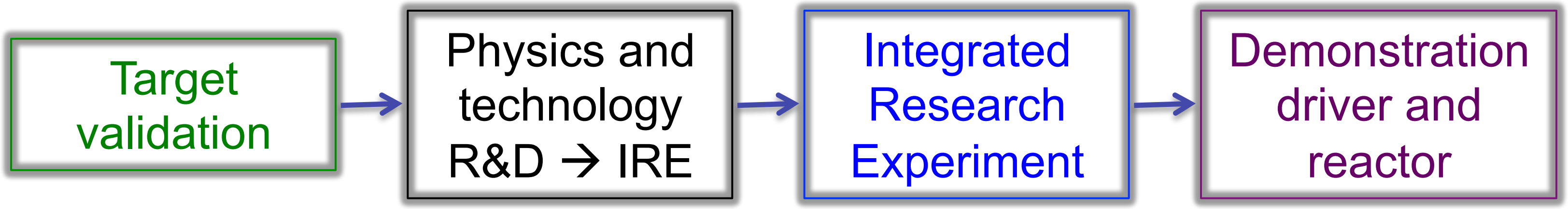


from The National Academies Press:
http://www.nap.edu/catalog.php?record_id=18289

Heavy-Ion-Beam Drivers

Conclusion: Demonstrating that the Neutralized Drift Compression Experiment-II (NDCX-II) meets its energy, current, pulse length, and spot-size objectives is of great technical importance, both for heavy-ion inertial fusion energy applications and for high-energy-density physics. (Conclusion 2-7)

Conclusion: Restarting the High-Current Experiment to undertake driver-scale beam transport experiments, and restarting the enabling technology programs are crucial to re-establishing a heavy-ion fusion program. (Conclusion 2-8)



Roadmap for Heavy Ion Fusion (NRC report on Prospects for IFE, p. A-61)

Laboratory-scale ignition on NIF or elsewhere …convincingly connected via computer simulations and existing ion target data, to high gain (G > 30) ion-driven targets.

Show that NDCX-II accelerator meets its designs goals… Performance matches theory and simulation…Validation of the accelerator and beam physics codes at increasing intensity.

By restarting and upgrading HCX: Transport of driver-scale beam charge density in magnetic quadrupoles without serious degradation of beam quality must be demonstrated and provide further validation for beam transport codes.

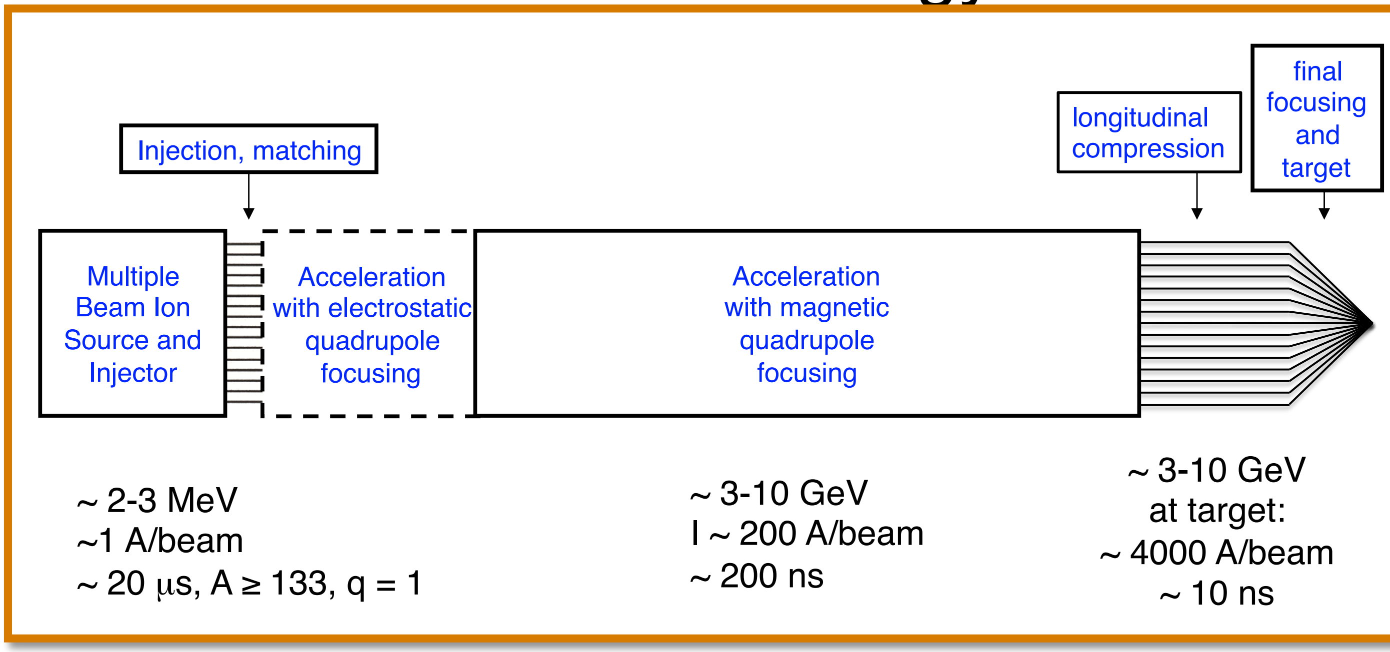
Technology and cost: Ion sources, magnetic quadrupole arrays, high-gradient insulators, high-voltage pulsers, must be further developed to demonstrate adequate cost, reliability, durability, voltage gradient, and efficiency. 10 Hz, 10^9 shots.

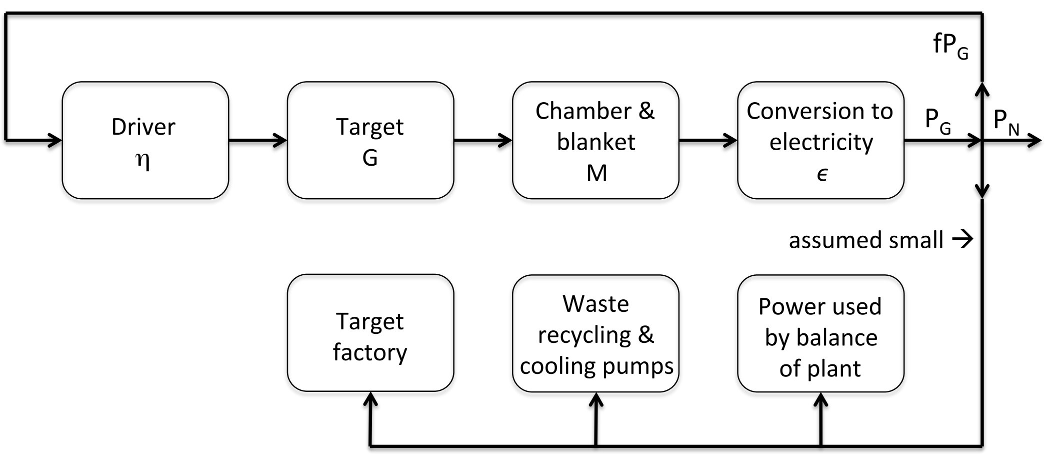
Produce a complete design of a final focusing system that rigorously meets all known requirements associated with beam physics and shielding.

Decision: If success above [including cost considerations]: construct a 10 kJ to 100 kJ accelerator, initial step of a fusion test facility. Validate the performance of scaled hohlraums and/or adequate hydrodynamic stability for directly driven ion targets.… demonstrate efficiency•gain, $\eta G > 10$.

Decision: Construct a full-scale accelerator driver. Demonstrate an $\eta G > 10$.

Induction linear accelerator driver for HIF: Schematic and energy flow



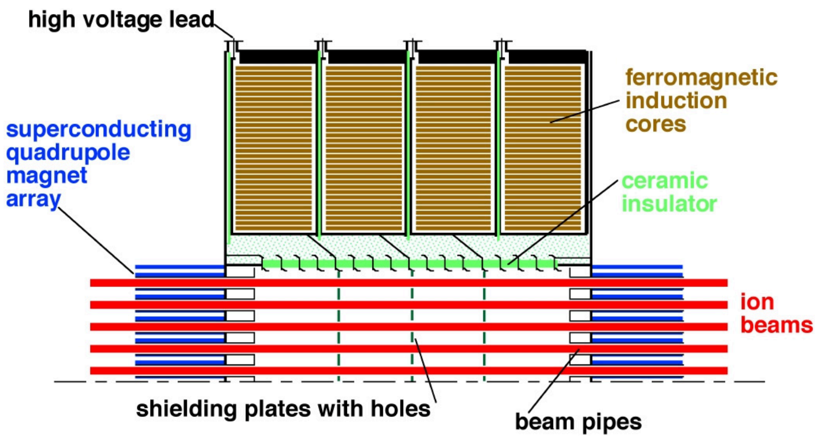


P_G = gross electrical power
P_N = net electrical power
Assume $f < 0.2$, $P_N \approx P_G(1-f)$

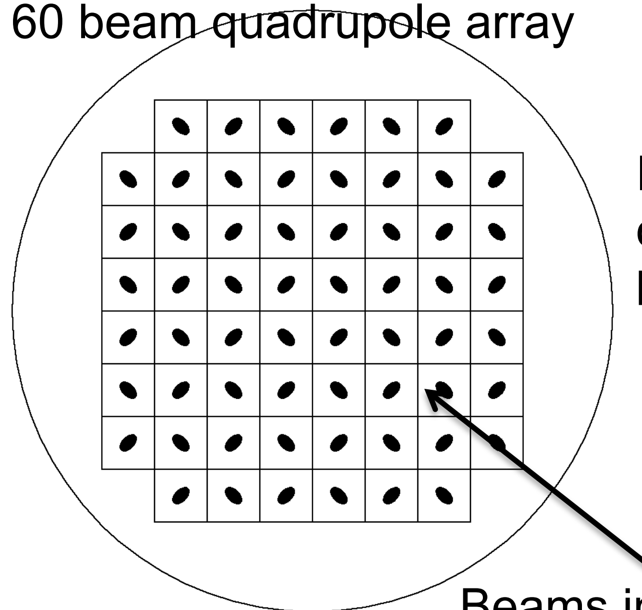
$\eta G > 10$, $G = 50 - 150$
$\eta = 0.2 – 0.4$
$M = 1.1 - 1.3$
$\varepsilon = 0.3 - 0.5$

Research on key components of induction linacs for HIF are needed to reduce risk

Schematic of one-half of a lattice period in a multi-beam accelerator



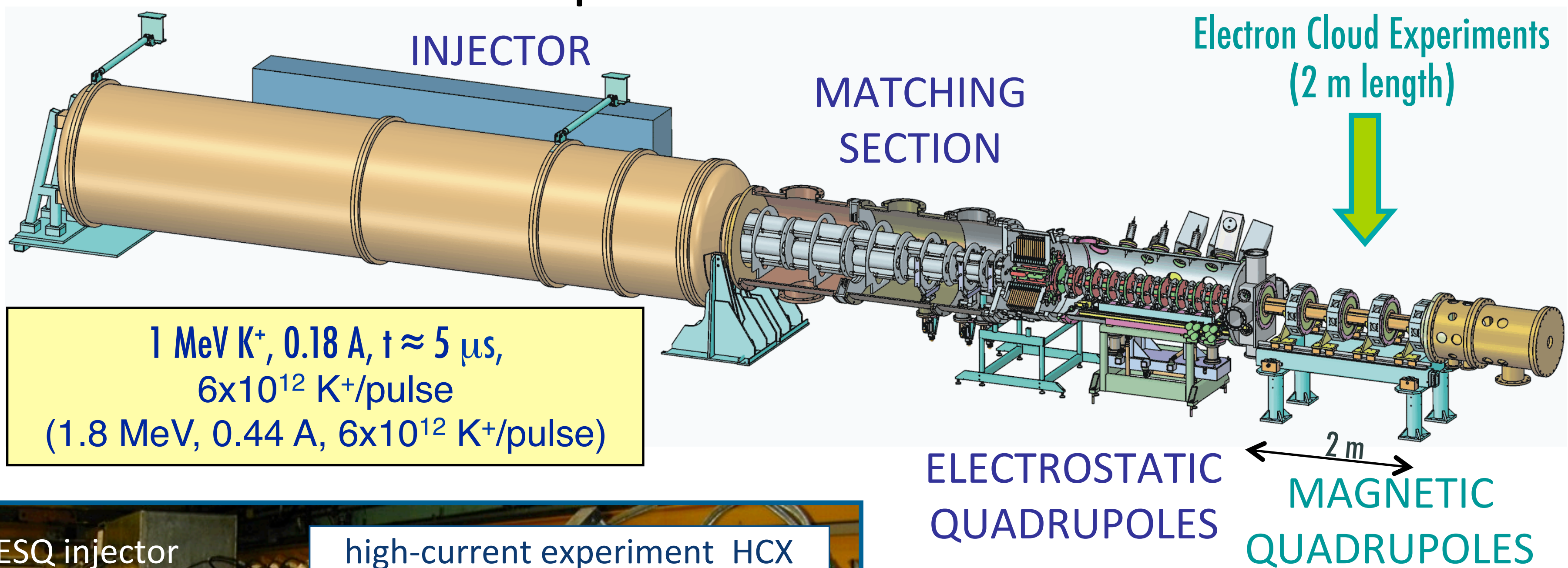
Schematic cross section of a 60 beam quadrupole array

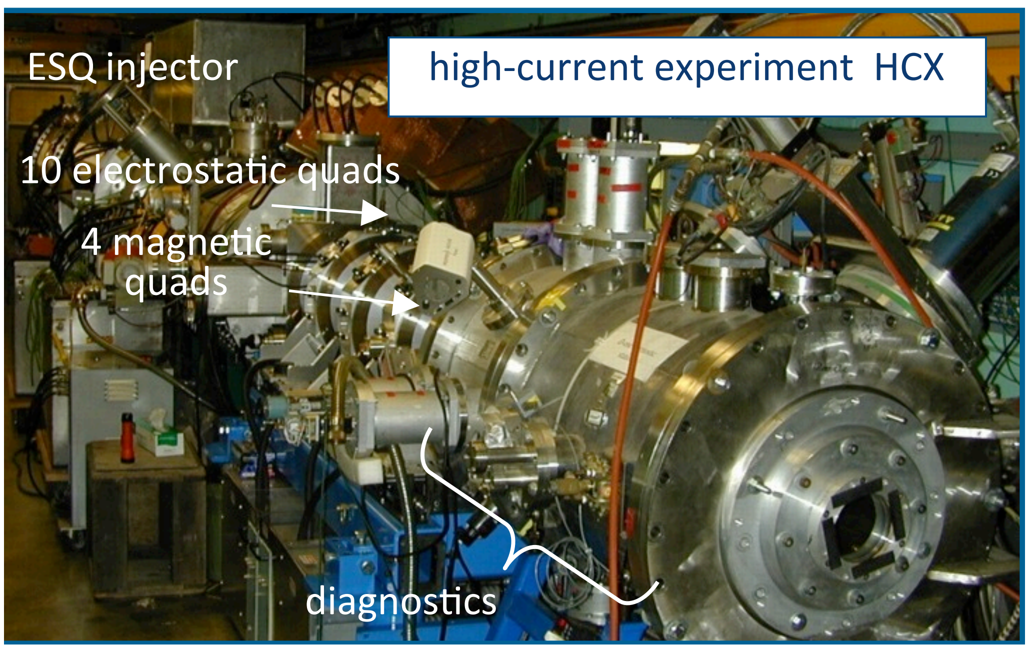


Alternating polarity of quadrupoles maximizes the flux sharing and minimizes the needed conductor.

An integrated acceleration module has yet to be built.

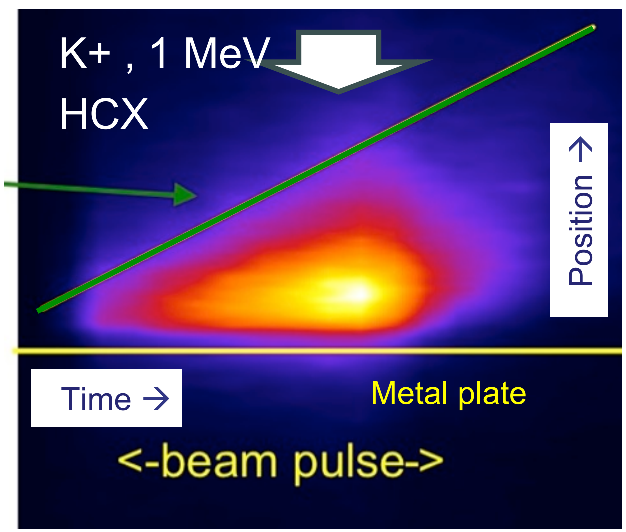
HCX at LBNL: Injection, matching, low-energy transport at HIF driver scale





Ions, e-, particle loss, desorption:

$v_{cloud} \approx 1.5$ mm/μs, mostly H_2



Some recent publications

1. ***Towards pump–probe experiments of defect dynamics with short ion beam pulses,*** T. Schenkel, et al., NIM B315 (2013), http://arxiv.org/abs/1211.6385
2. ***Reliability of temperature determination from curve-fitting in multi-wavelength pyrometery,*** P. Ni, et al., Laser Part. Beams 31 (2) 333 (2013) http://dx.doi.org/10.1017/S0263034612001103
3. ***Initial experimental evidence of self-collimation of target-normal-sheath-accelerated proton beam in a stack of conducting foils,*** P. Ni et al., Phys. Plasmas 20, 083111 (2013) http://dx.doi.org/10.1063/1.4818147
4. ***Commissioning And Initial Experiments On NDCX-II,*** S.M. Lidia et al., Proc. PAC'13, http://jacow.web.psi.ch/conf/pac13/prepress/MOPAC19.PDF
5. ***Accelerators for Inertial Fusion Energy Production,*** R.O. Bangerter, A. Faltens, P.A. Seidl, Rev. Accel. Sci. and Tech., V6, in press.
6. ***Research and development toward heavy ion driven inertial fusion energy,*** P.A. Seidl, J.J. Barnard, A. Faltens, A. Friedman, Phys. Rev. ST-AB (2013) http://link.aps.org/doi/10.1103/PhysRevSTAB.16.024701

43 refereed papers in: Proc. 19^{th} Int'l. Symp. on Heavy Ion Inertial Fusion, NIM A V733 (2013).

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