Working group 1: our original task

1. **Drivers/ Experiments (Andrew Ng, John Barnard, chairs)**

What are the advantages and disadvantages of each method?
What are the opportunities for collaboration?
What target regimes are accessible for each method?

Participants: Sam Mao, Art Molvik, Craig Olson, Dale Welch, Tim Renk, Dave Rose, Prabir Roy, Adam Sefkow, Richard Sheffield, Roman Tachyn, Peter Seidl,Naeem Tahir, Matthew Thompson, Itoki Yoneda

Working group 1: what we actually did

1. Tim Renk: Characterizing the RHEPP-1 oxygen beam and its effects on sold targets

2. Adam Sefkow: NDCX1-A parameter optimization simulations: Moving towards 1 eV target heating for WDM experiments

3. Dale Welch: Avoiding preheat in a Warm Dense Matter experiment

4. Richard Sheffield: Warm Dense Plasmas using the proton beam from the PSR

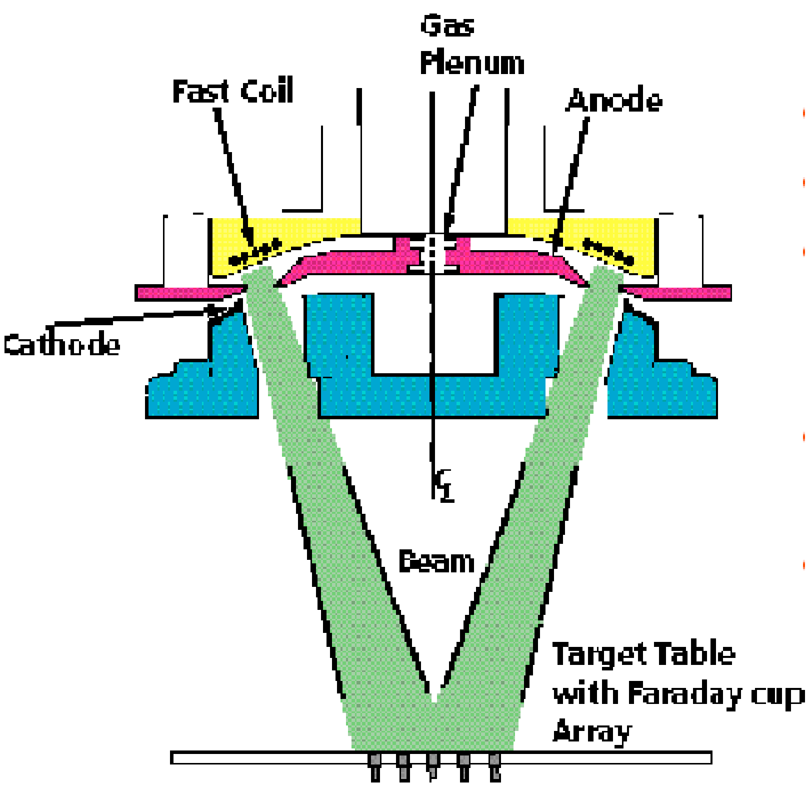
5. Roman Tachyn: Synchrotron radiation source configurations for the fast x-ray ignition of inertial confinement fusion (ICF) targets: application to WDM heating

Questions:

1. What are the advantages and disadvantages of each method?
2. What are the opportunities for collaboration?

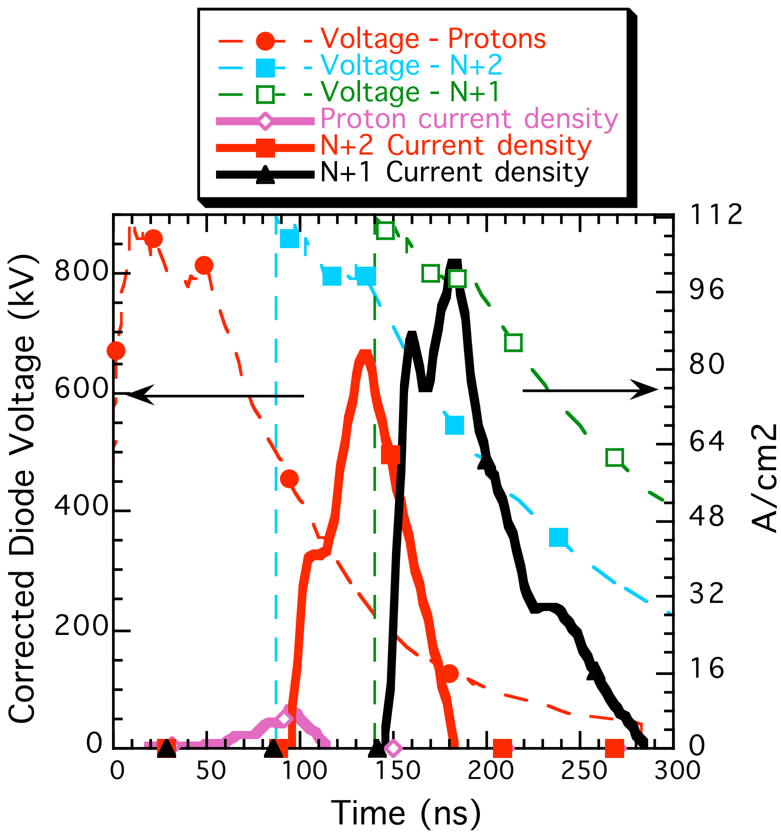
1. Tim Renk and Craig Olson: Characterizing the RHEPP-1 oxygen beam and its effects on solid targets

The MAP (Magnetically Confined Anode Plasma) Ion Source is used for surface modification experiments on RHEPP-1



- 500-850 kV
- < 350 A/cm²
- Beams from H, He, N_2, O_2, Ne, Ar, Xe, Kr, CH_4
- Overall treatment area ~ 100 cm²
- Diode vacuum ~ 10^{-5} Torr

Nitrogen injection into MAP produces 3-component beam of mostly N++, N+

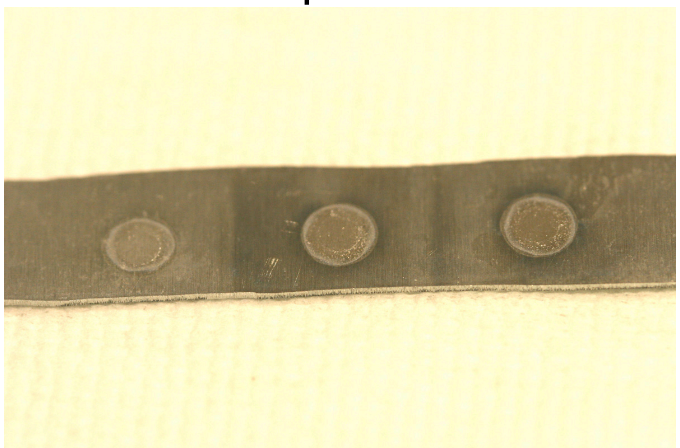


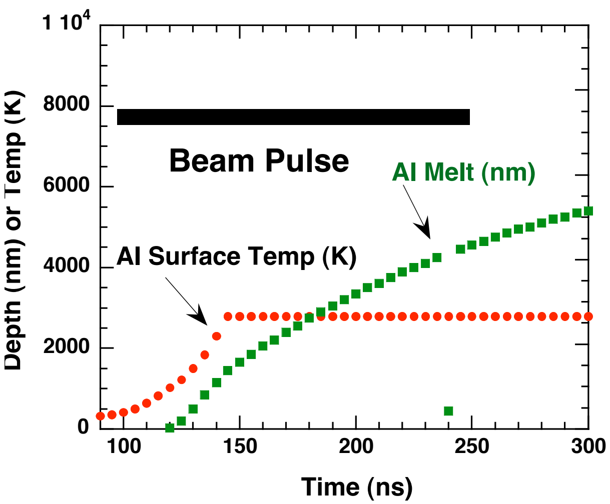
Shot 31661

- Beam predominantly N++ and N+ after small proton pulse at front
- Peak voltage = 850 kV
  Peak current density (total) ~145 A/cm^2
- Total fluence = 7.9 J/cm^2 - will ablate almost all materials
- Total pulse width at target ~ 200 ns
- Ion range (TRIM):
  N+ 0.9 μm, N++ 1.2 μm
- Oxygen, Neon beams similar

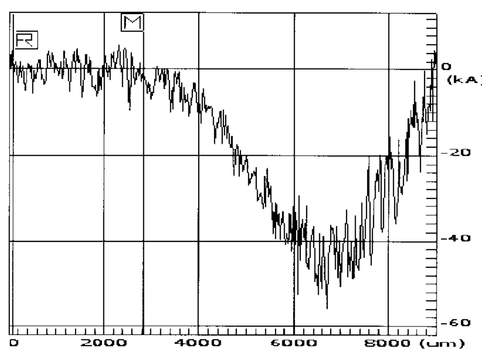
Single Oxygen pulse makes 4 μm-deep crater in Al 2024-T6

Photo - 3 Al melt spots





Al Melt Temp 933K **Vapor Temp 2793K**



Center spot - Profilometer scan

Material: Al 2024-T6

Three 4mm countersunk holes 1.3 cm apart in Ta aperture plate aperture-target dist = 3.5 mm

Profilometer: 4 μm-deep ablation pit

SIM: I-d Heat Flow Code, energy input from TRIM, then bulk properties. Does NOT model ablation

Beam pulse 0-250 ns, 6 J/cm^2

- H - very small, 20K rise by 90ns
- Oxy - ablation temp (2793K) by 140 ns

Surface below 2793K by 660ns, Al melt depth reaches 10 μm by 1.5 μsec. Peak SIM Al temp = 9500K

Ta: 6J/cm^2 simulation exceeds 12,000K (low Ta thermal conductivity)

Al melt duration well beyond 10 μsec

Summary

RHEPP-1 with active ion source can generate intense ion beams of total currents ~ 5 kA, peak currents ~ 250 A/cm^2, with variable dose over a ~150 cm^2 target area. Beam pulsewidth ~ 150 - 400 ns

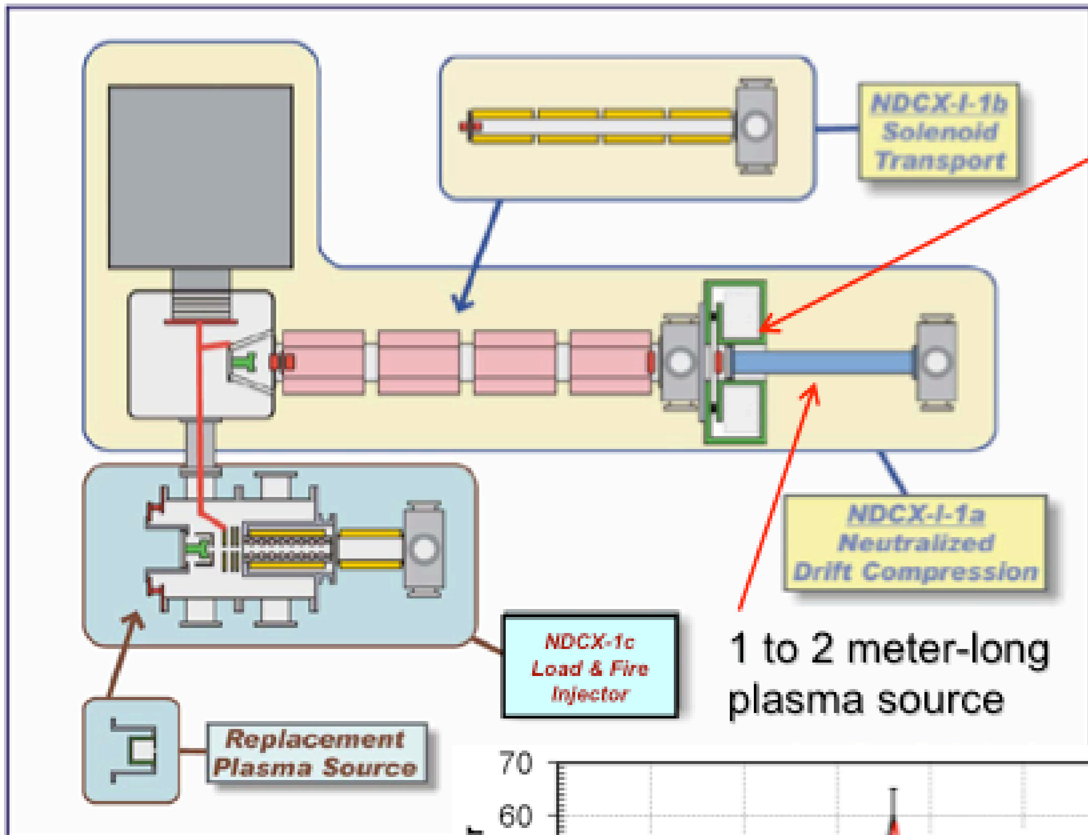
Present oxygen beam can ablate any metal, over a 50-500 ns timescale. Peak effective temperatures approach 10,000K (~1 eV).

Beam optics studies indicate possible paths for improvement. One idea is to 'fill' the anode annular gap with a screen.

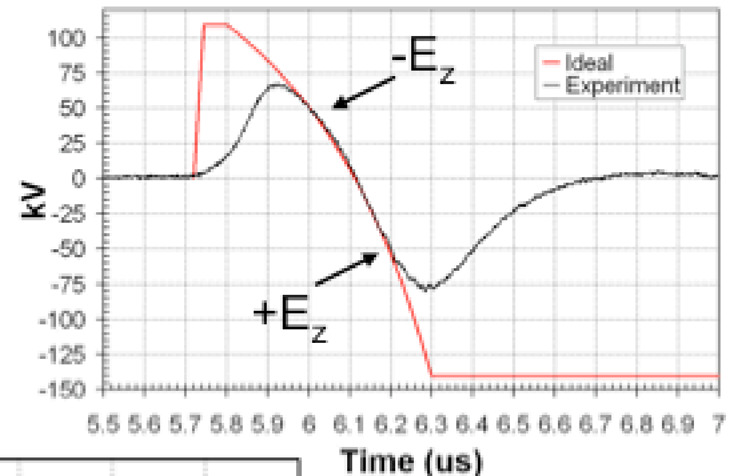
RHEPP/MAP can be considered either for 1) preliminary effects experiments, or 2) as a test-bed for diagnostic development. Preference is for real-time diagnostics (not time-integrated)

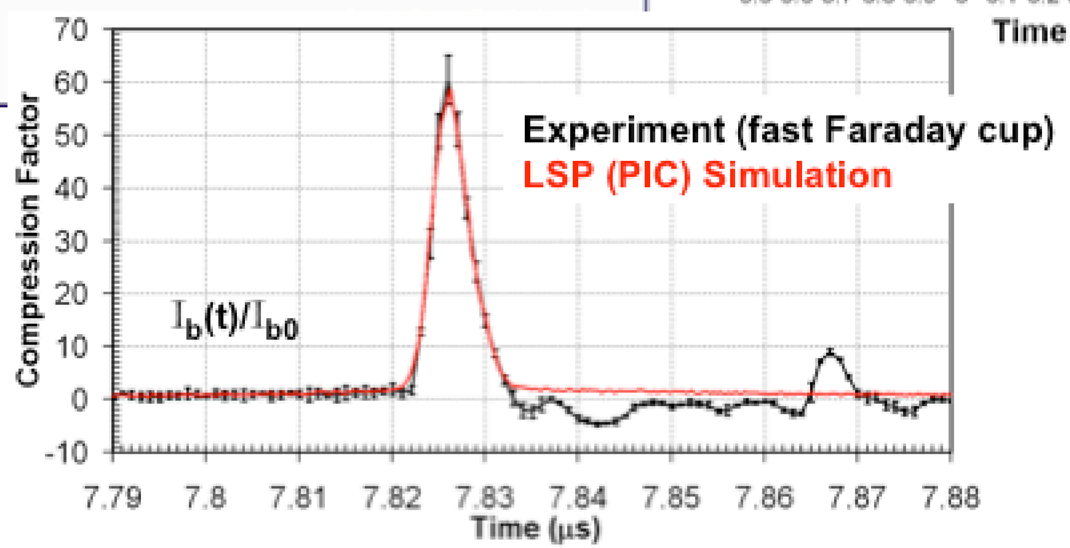
2. Adam Sefkow et al: NDCX1-A parameter optimization simulations

60X Longitudinal compression achieved in NDCX-1A experiments

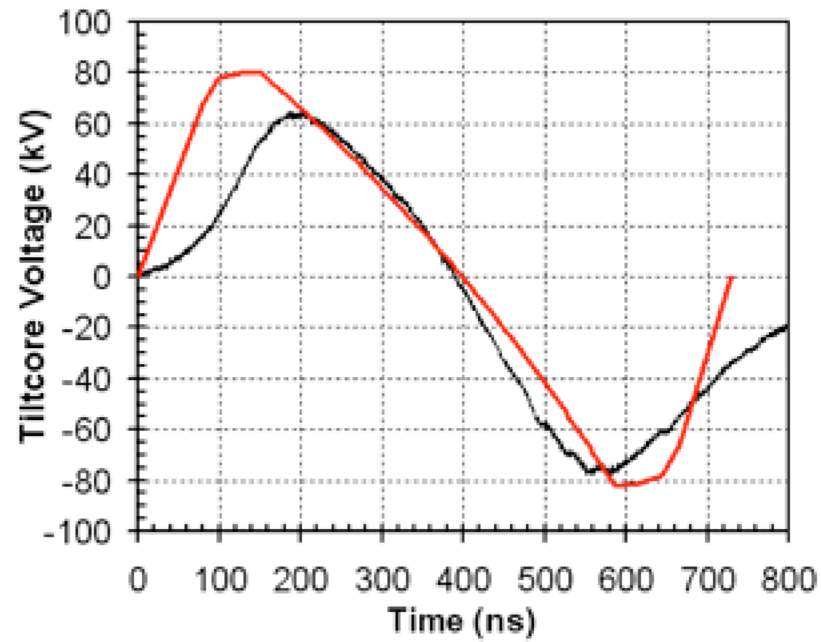


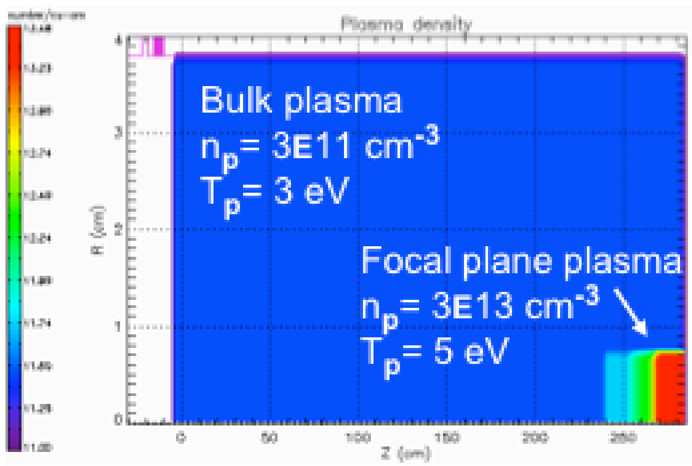
Single-gap linear induction accelerator (induces pulsed E(t) along axis of beam), also called the "tiltcore" because it imposes a head-to-tail velocity tilt on the passing ion beam via a time-dependent voltage waveform applied across the gap.



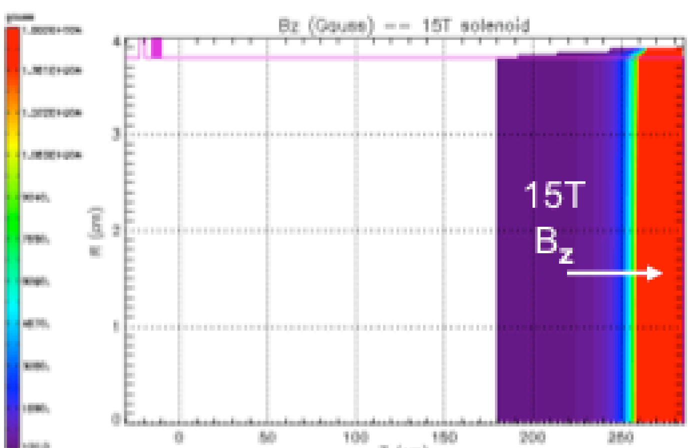


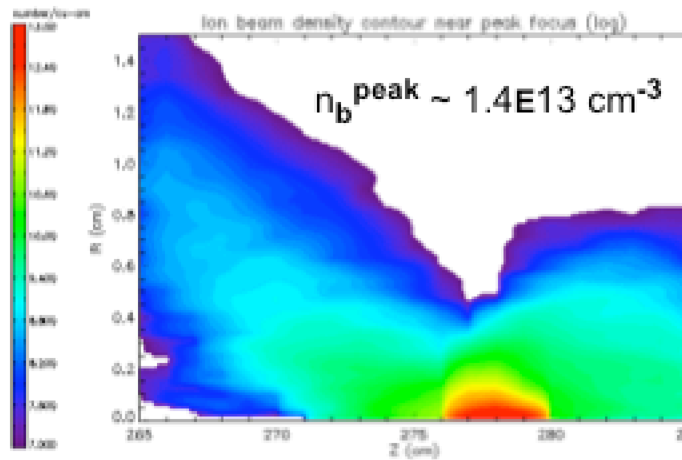
- 400 keV K^{+}, 80 mA, r = 1.9 cm, T = 0.2 eV
- 0.6 μs initial pulse length
- 2.90 m focal length, 21.2% tilt (in red, on right)
- B = 15 T for transverse focusing
- n_p = 3E11 cm^{-3} bulk to 3E13 cm^{-3} in focal region
- EM kinetic simulation, conserves energy well





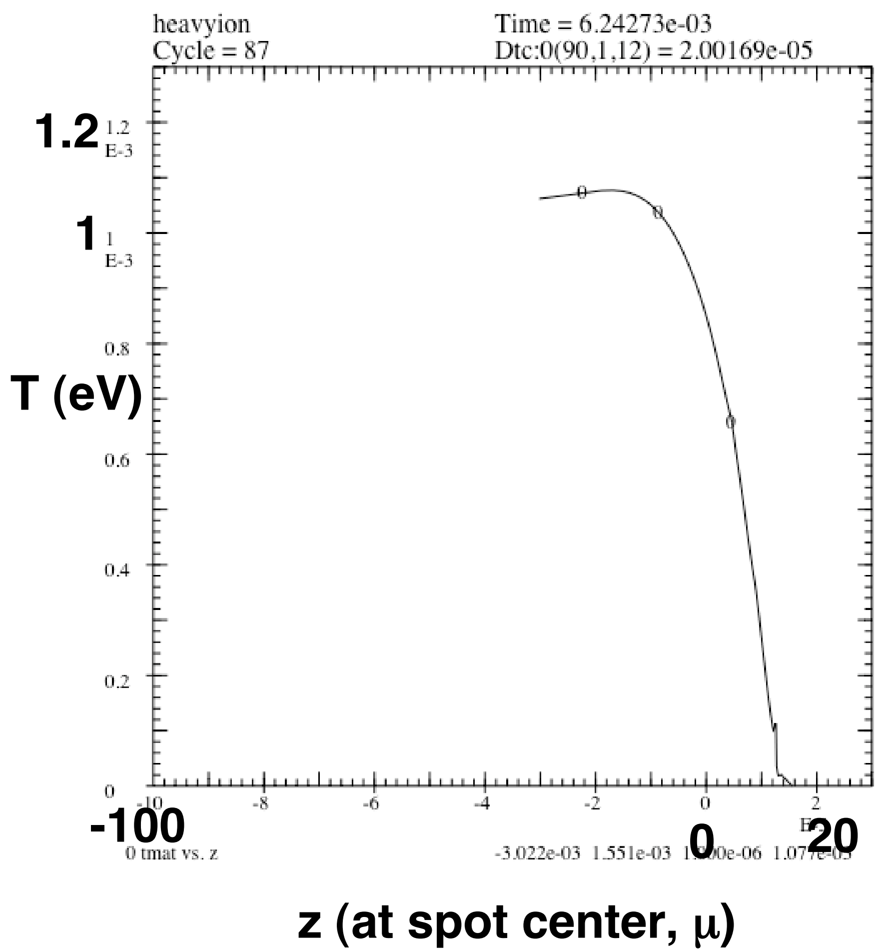
Induction module waveform (above):
Experimental: 320 keV K^{+}, 20mA → **60X**, *4.3ns* (f=2.34m)
Simulation: 400 keV K^{+}, 80mA →**125X**, *3.0ns* (f=2.90m)

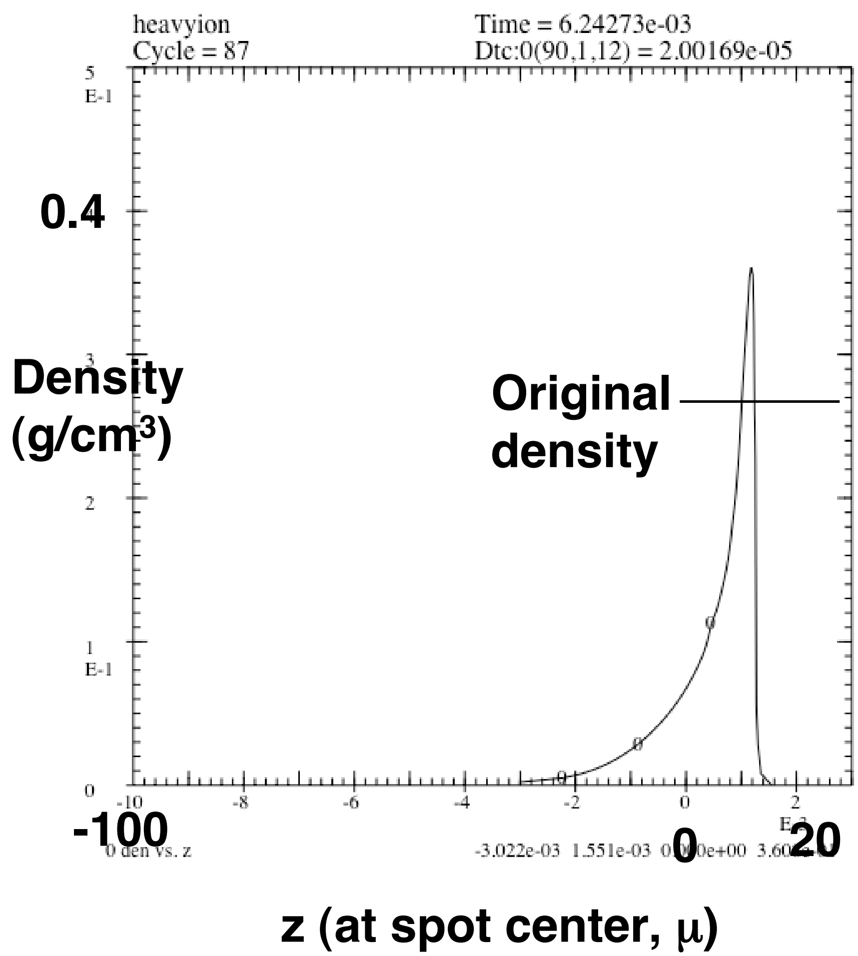




Adam Sefkow et al: NDCX1-A parameter optimization simulations: Moving towards 1 eV target heating

HYDRA shows a maximum temperature of 1.1 eV at 6.2 ns (for a 10 μ thick, 10% density Al foil)

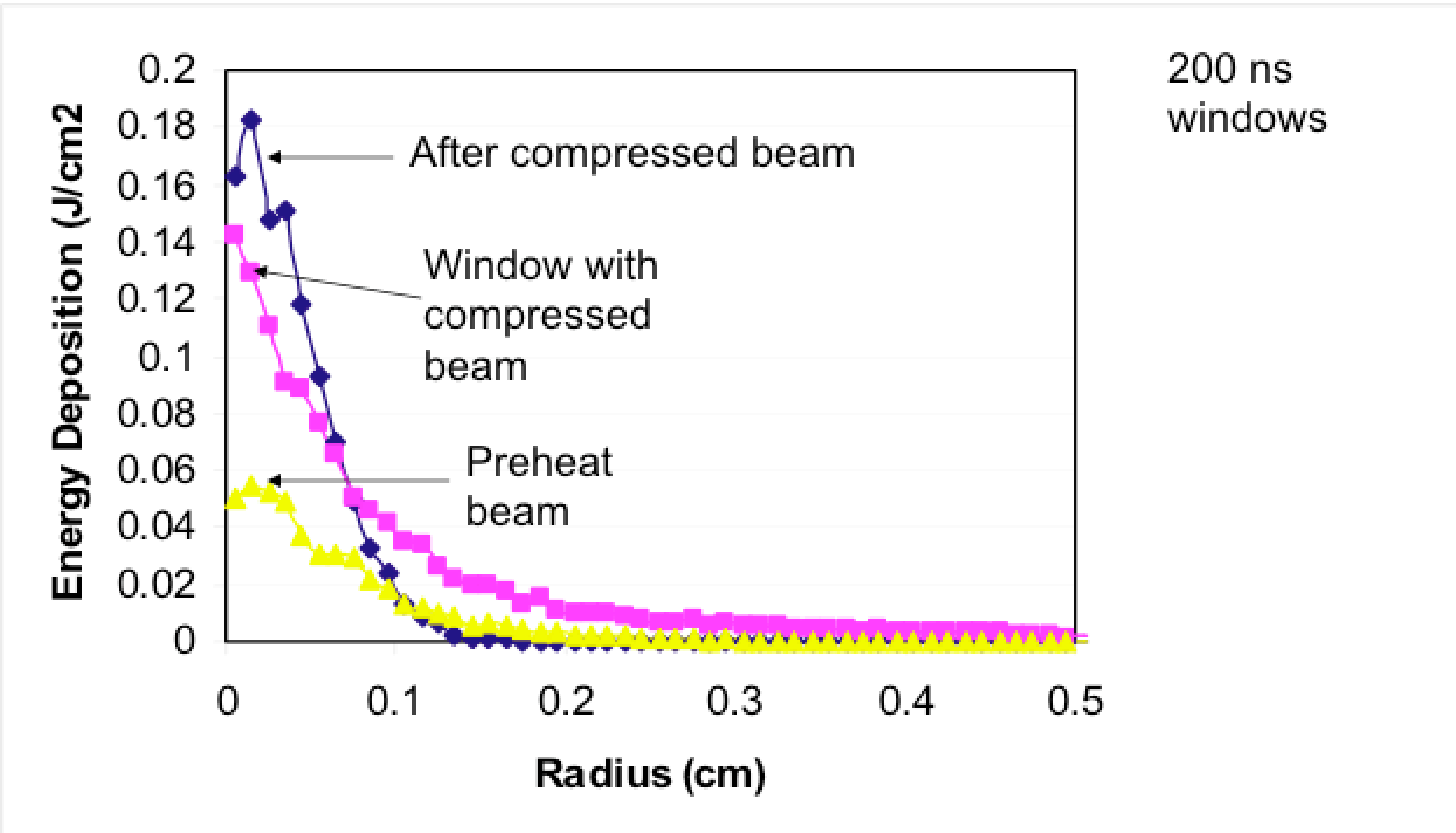




3. Dale Welch and David Rose: Avoiding preheat in a Warm Dense Matter experiment

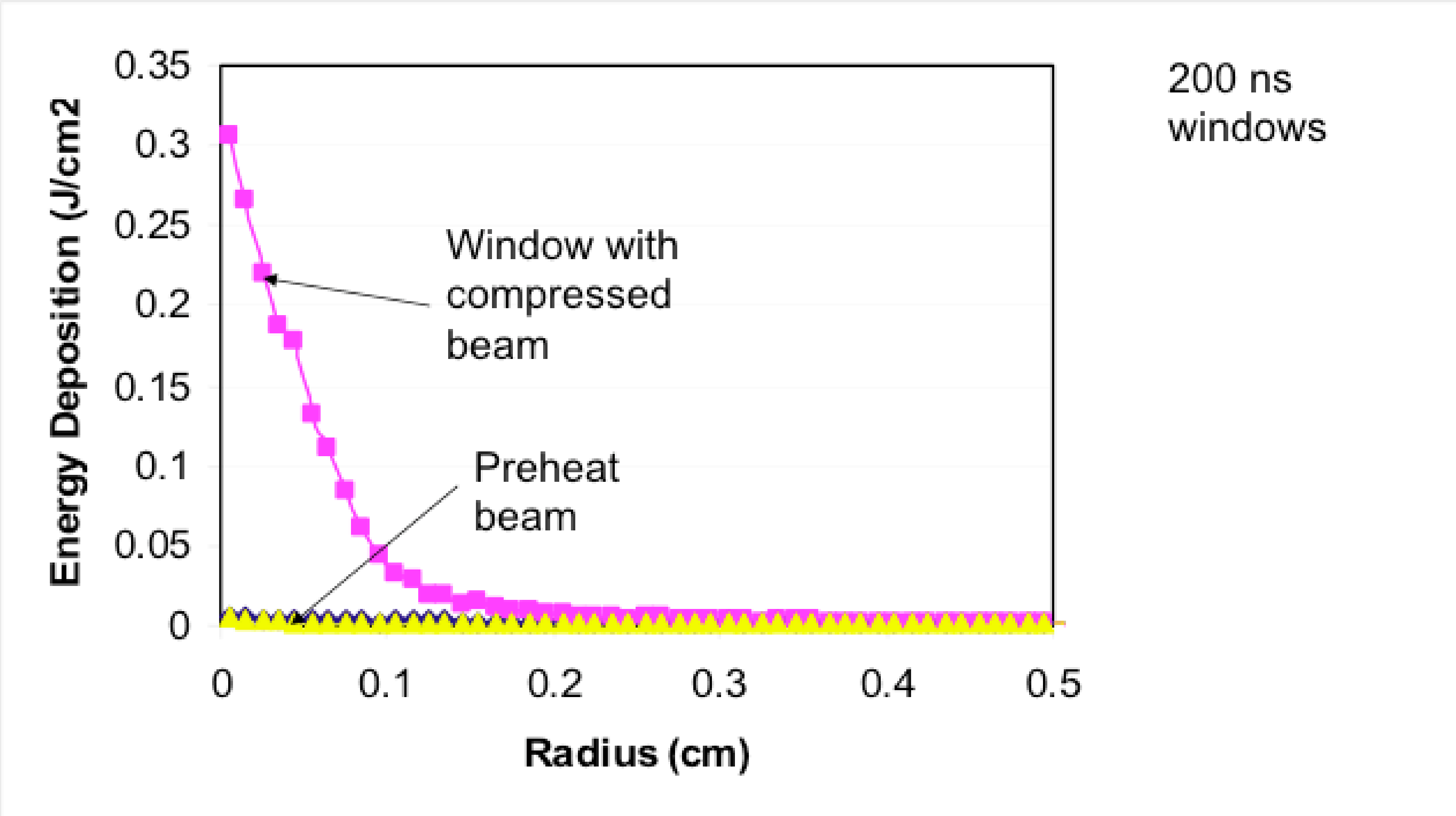
Nominal focus gives terrible contrast

- Beam given a 8.5 milliradian angle, compressed portion of beam reaches solenoid with a 1.5 cm radius
- Focus tighter for uncompressed beam, terrible contrast



Over focus of beam

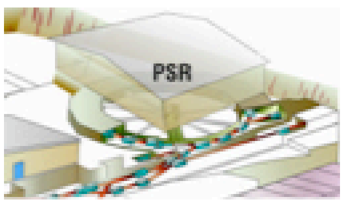
- Beam given a 19 milliradian angle – uncompressed beam focuses before solenoid
- Beam tightest at axial compression, contrast excellent
- Should be able tolerate 1 microsecond pre-pulse

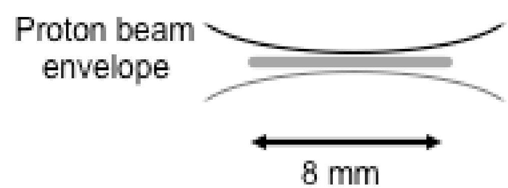


3. Dale Welch and David Rose: Avoiding preheat in a Warm Dense Matter experiment

The PSR pulse can be used to generate HEHD states comparable to the proposed SIS-18 experiment

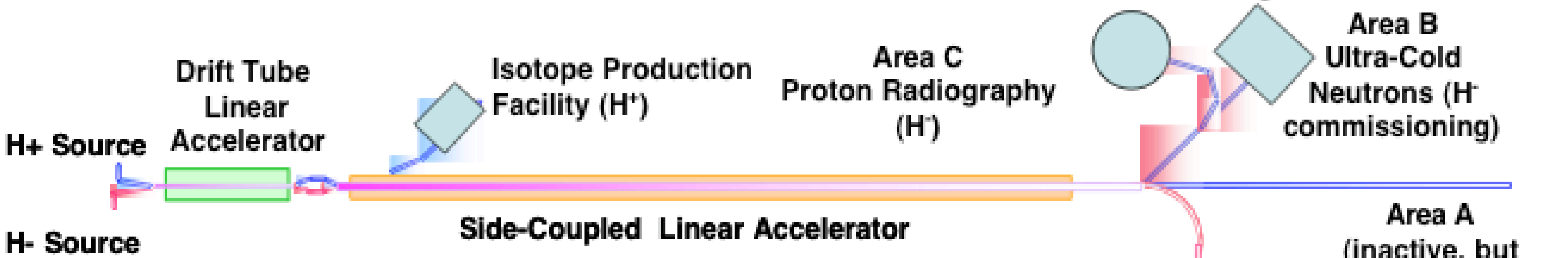
- The PSR beam has the following demonstrated performance: 8μC/pulse, 330 ns pulse length, $\varepsilon_h = 6.3\ \pi$ mm-mrad, $\varepsilon_v = 10.3\ \pi$ mm-mrad, 800 MeV.
- Target: Pb wire 0.22 mm radius and 8 mm long
- Beam at target: minimum 0.3 mm radius that expands to 0.33 mm at wire end and deposits 11 MeV in the Pb.

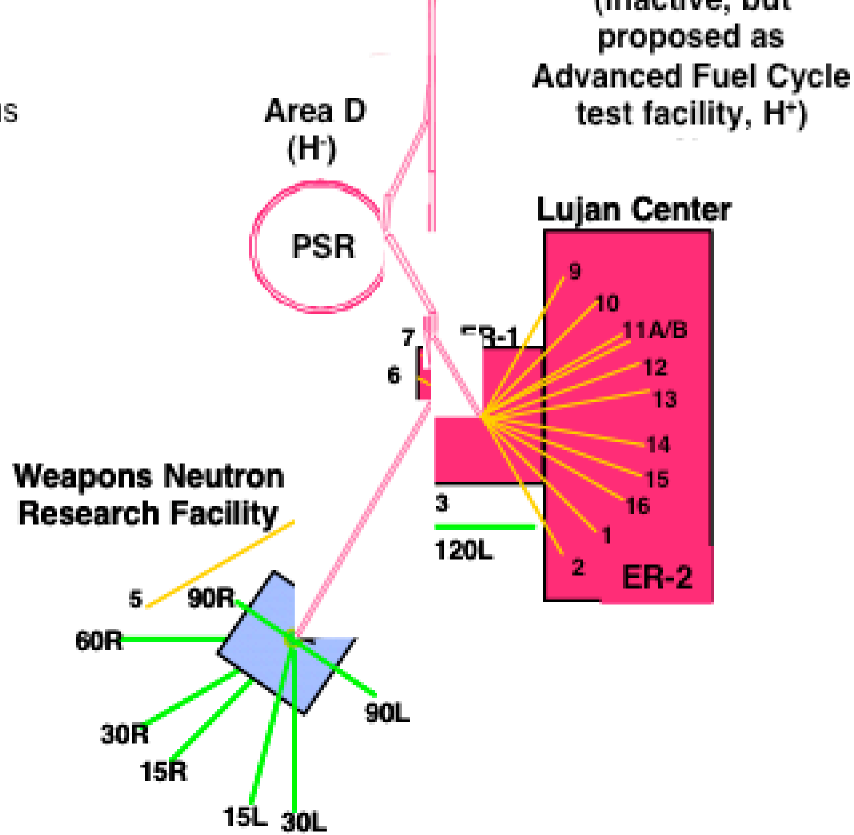




- Energy partitioning
  - Heating and vaporizing wire: 1.1kJ/gr
  - Residual energy for plasma excitation: 2.8 kJ/gr.
- For comparison, proposed SIS-18 experiment has
  - 0.3 mm radius and 3 mm long Pb target
  - Heating and vaporizing wire: 1.1kJ/gr
  - Residual energy for plasma excitation: 3.2 kJ/gr.

The LANSCE user facility operates for 6-8 months per year in 24/7 mode with unmatched versatility worldwide





Proton Linear Accelerator

Two ion sources produce H^+ and H^- beams for simultaneous acceleration

0.75 MeV to 100 MeV Drift Tube linac

100 MeV to 800 MeV Side-Coupled linac

Isotope Production Facility

Medical radioisotope production using 100 MeV protons

Proton Radiography Facility

Pulsed proton beam for static and dynamic radiography

Lujan Center

Moderated neutrons for neutron scattering and nuclear science

Weapons Neutron Research Facility

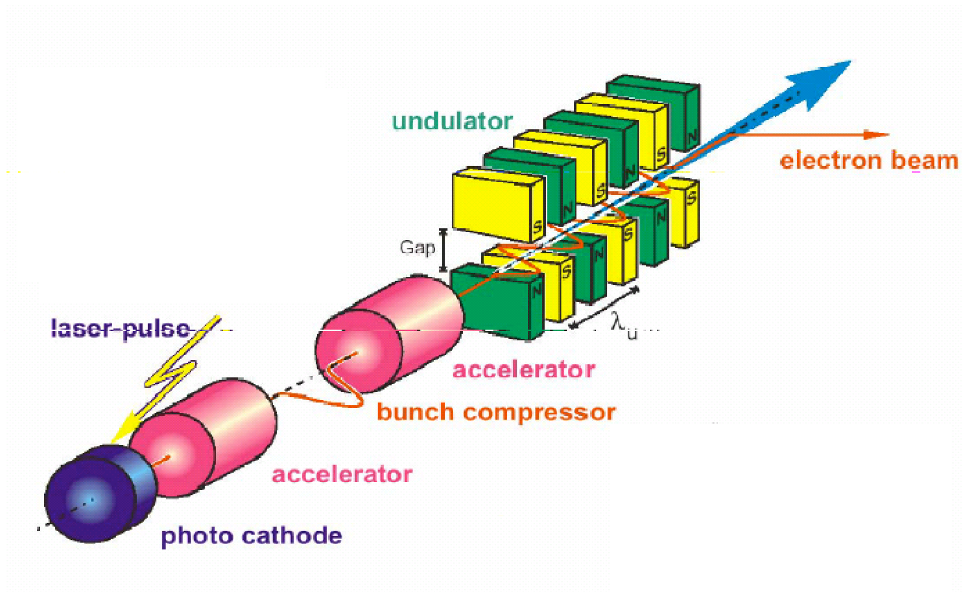
High-energy neutrons and protons for nuclear science and applications

Ultra Cold Neutron Facility

Fundamental physics experiment in commissioning

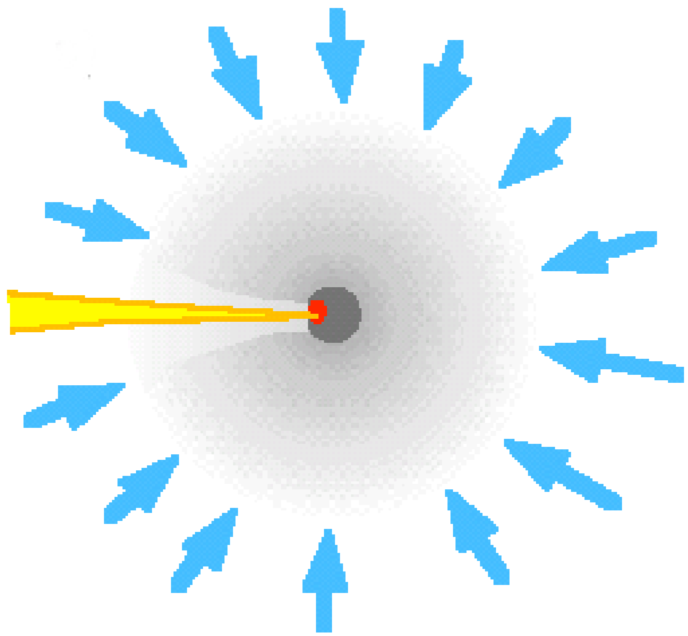
The LINAC ICF X-Ray source

- **Requirement**: deliver ~ 100 Joule, ~10 ps pulse of 3-10 keV photons into 10-20 micron diameter volume
- **Method:** focus synchronized Energy Recovery Linac (ERL) driven wiggler pulses into target volume
- ERLs using laser-driven photocathode (pc) rf guns can easily produce ~10 ps electron bunches synchronized to ~1 ps.



R. Tachyn and V. Shlyaptsev: Synchrotron radiation source configurations for the fast x-ray ignition of inertial confinement fusion (ICF) targets: application to WDM heating

Fast ignition with X-ray source



X-rays pass through plasma corona, lower density debris and hohlraum walls and deliver energy exactly at the dense compressed core.

- 100% absorption right at the dense spot, highest efficiency,
- no hole boring or cone geometry needed.

The advantages of X-ray fast ignitor approach

- **Almost complete utilization of x-ray source energy for photons in 2-4 A range, 1-2 orders smaller source energy requirements** as opposed to regular approach to fast ignition which supposed to produce multi-MeV electrons which have small absorption crossection and pass through dense core almost without interaction.

- **Very directional deposition of heating energy exactly at the dense spot.** The keV x-ray photons are absorbed exactly at high compression core while all other material on the pass are almost completely transparent. Surrounding areas are transparent for x-rays due to N^2 density dependence of absorption coefficient. **No hot electrons, self-focusing and filamentation problems.**

- Both the electron and ion mean free paths in hot spot are much smaller than spot dimension, at 5keV they are of the order of 100 A, which means **high locality of x-ray energy deposition** (electron collision time of thermal electrons is very short, less than 10-15 fsec) which assures **high predictability and reliability of modeling of this concept. The interaction of x-ray radiation with plasma and hydrodynamics remain classical** hence simplifying many aspects of physical and numerical models.

- **Potentially high focusability of X-ray source radiation into small focal spot** of required dimensions ~10 microns.
- **All other advantages of fast ignitor concept are valid** (smaller and cheaper laser driver for initial compression, less symmetry constraints, instabilities and turbulences are much less influence).

Roman Tachyn and V. Shlyaptsev: Synchrotron radiation source configurations

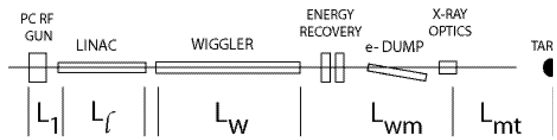
The X-ray source

- The required energy can be obtained by multiplexing ERLs

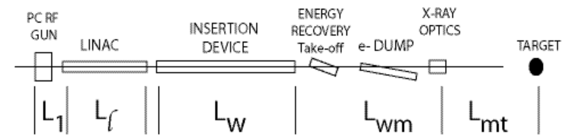
- Extraction-enhanced (tapered) FELs may offer prder-of-magnitude higher energy (>5 kJ)

$$N \cong \frac{E_{IG}[J]}{\eta_{FEL} E[GeV] Q_B^2 [nC]}$$

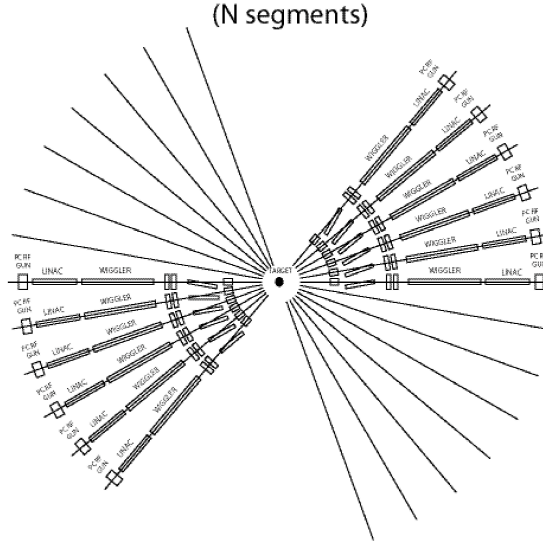
ICF X-RAY IGNITER SEGMENT



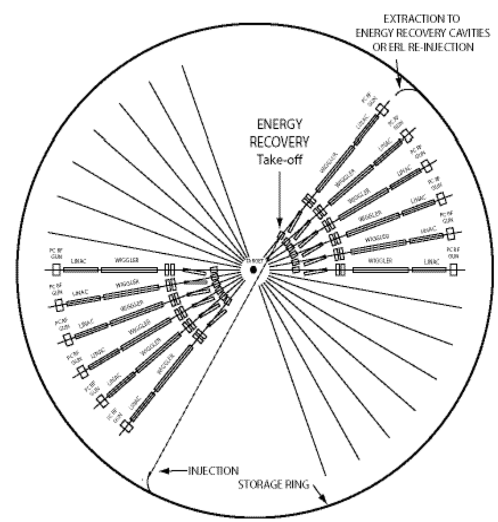
ICF X-RAY IGNITER SEGMENT WITH BEAM TAK-OFF TO BEAM STORAGE



ICF X-RAY IGNITER FACILITY (N segments)



ICF X-RAY IGNITER FACILITY WITH INTERBUNCH BEAM STORAGE FOR ERL EFFICIENCY ENHANCEMENT



Roman Tachyn and V. Shlyaptsev: Synchrotron radiation source configurations

1. What are the advantages and disadvantages of each method?

Particle beams

\+ Any solid-phase target material (metal or insulator)
\+ Probably know beam deposition accurately (1%)
\+ beam deposition is ~ uniform over 1-100 micron depth (~ 1 MeV/u ions), ~ 1 mm (5 MeV electrons), ~2 mm (~GeV ions)
\+ Probably beam dE/dx doesn't change more than 5 % for T < 1 eV
\+ Probably produces LTE state in targets, i.e., doesn't heat a minority population of atoms or electrons to high temperature
\+ Ion beam itself can be used as diagnostic of WDM (charge state, energy loss)
\+ Good synergy with HIF research strategy (for ions)
\+ Can be high rep rate
\- Existing beams have low total energy, low-moderate power, > nsec pulse
\- Need to coordinate diagnostics with beam, e.g., timing probe pulses
? Plasma effects on sample
? Drive shock with ion beam

Ultra short pulse lasers

+ Very rapid heating
+ Enormous energy-density is easy (low cost)
+ Good diagnostics by pump-probe technique
+ Existing systems do high rep-rate experiments --> data-rich
+ Laser beam can be converted to secondary particles or photons

0 Electrons are heated at different rate than the ions
0 Some materials are too reflective (but if you have enough energy not a problem)

-Deposition is uniform only in ultra thin layer (although some materials have high deposition depths (such as transparent materials)
- Total energy input has fluctuations (but can be calibrated)
- Heating changes absorption in a way that's not a priori known (but total absorbed and reflected energy can be determined)

Electrical heating with single wires

+ Measure I(t), V(t) and therefore know the deposited energy
+ Large samples, low cost; high total energy is no problem

- Slow heating (microsecond range) due to switching/inductance limits
- Hydro during heating; current is non-uniform
- Mainly limited to metals
- Diagnostic access are difficult

q For isochoric experiments: Magnetic effects? MHD? Runaway electrons in low-density gas? Discharges?
0 For expanded state experiments: (low density experiments) not an issue.

Z-driven pulse power

+ Lots of energy
+ short pulse
+ large volume

- on a large facility with limited access; expensive experiments
- limited rep rate
- dedicated facility (to non-WDM research)

X-ray heating (accelerator driven, such as FEL's)

+ Volumetric heating with small gradients
+ Energy deposition profiling possible; focusing
- In some cases, heating will change the absorption coefficient
- Need to develop technology for integrated experiments (for hard X-rays)

Ion beam made from laser pulses (Petawatt driven)

+ Abundant energy available
q Will we know the deposited energy to 1%?
-Need big effort to characterize angular spread, energy spread, etc.
- Large energy spread
- Complex targets and/or experiments?

Main conclusion: No experiment is perfect; Comparison of results from various heating methods advances the field!!

2. What are the opportunities for collaboration?

There were many potential areas of collaboration:

1. **Use of Sandia REPP machine has clear potential for testing diagnostics in preparation for shorter pulse machines (such as NDCX).**

2. **Use of LANL PSR has clear connection to WDM experiments at GSI.**

3. **Sharing of diagnostics (VISAR, XUV spectroscopy, streak cameas etc.) should be explored (more to be said in Diagnostics working group.**

4. **GSI/HIFS VNL collaboration on foams**

Minimum action item: Sequence of near term experiments should be layed out so potential collaborators can determine where collaborations would be fruitful