For Chan Joshi

Interagency Task Force Workshop

Gaithersburg, Maryland

May 26, 2004

Beams Working Group Summary

Thrusts #4-6

Scientific objectives, milestones and resources

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Thrust Area 4:

Heavy-Ion-Driven High Energy Density Physics and Fusion

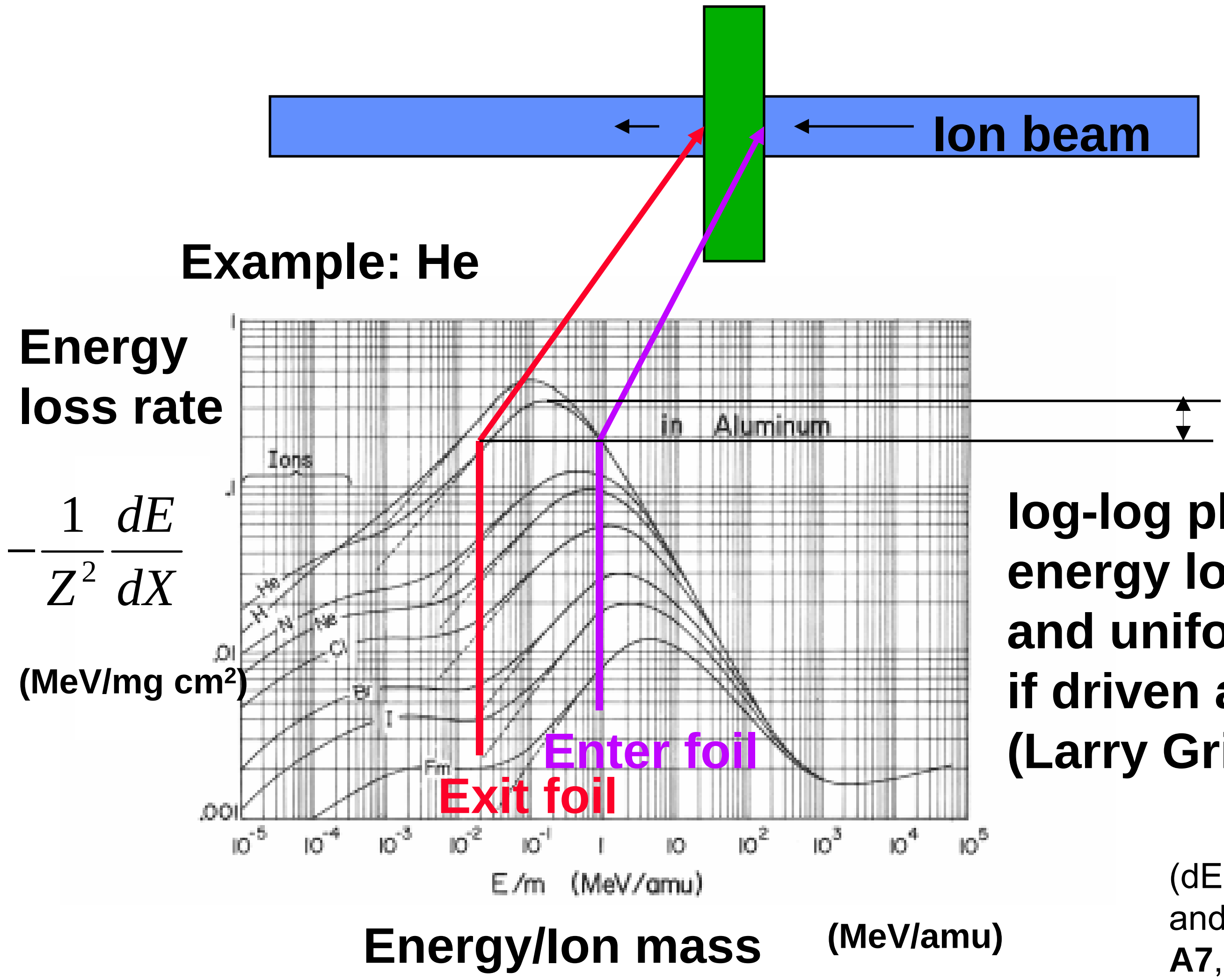
Grant Logan

Compelling Question for heavy ion thrust area:

How can heavy ion beams be compressed to the high intensities required for creating high energy density matter and fusion ignition conditions?

Strategy: maximize uniformity and the efficient use of beam energy by placing center of foil at the Bragg peak in dE/dx

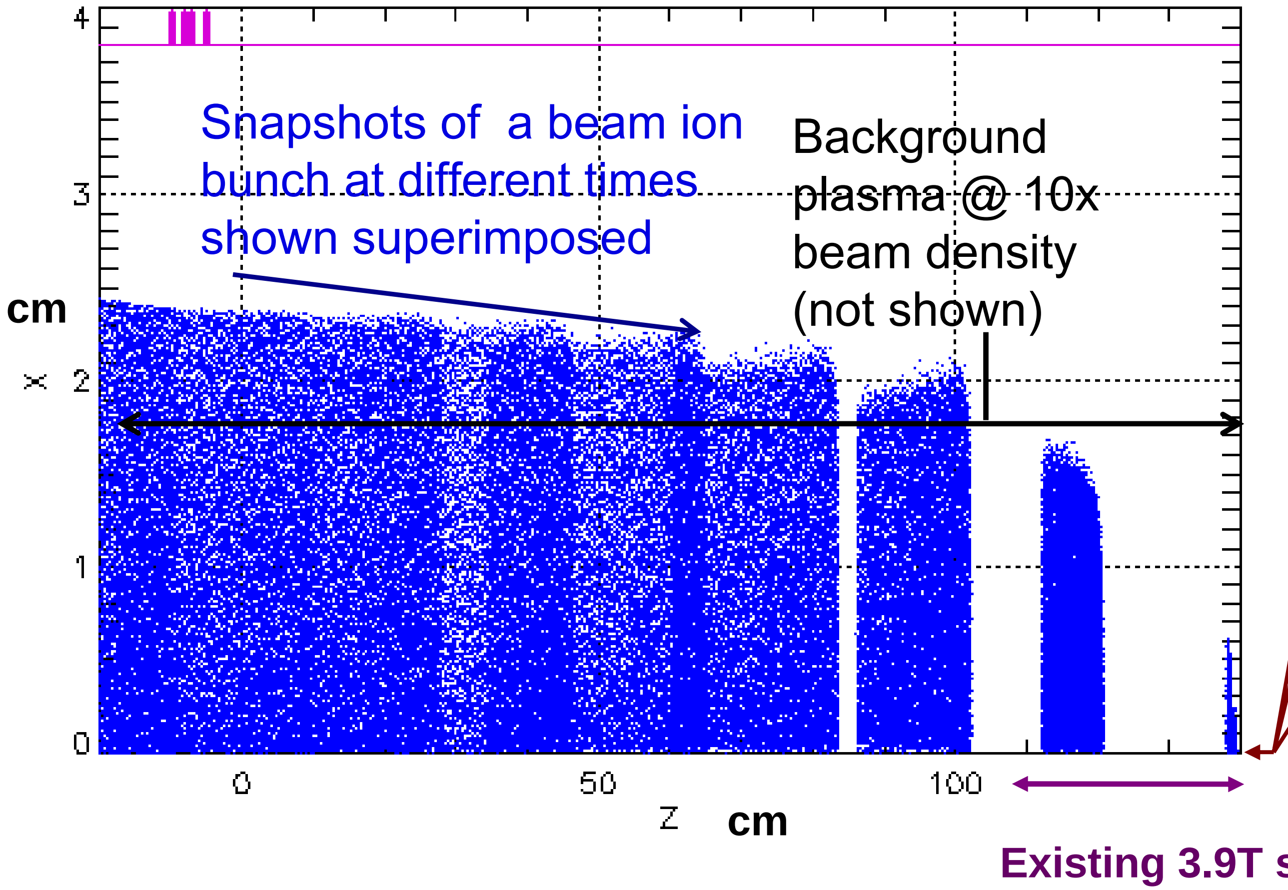
In simplest example, target is a foil of solid or "foam" material



log-log plot => fractional energy loss can be high and uniformity also high if driven at Bragg peak (Larry Grisham, PPPL)

(dEdX figure from L.C Northcliffe and R.F.Schilling, Nuclear Data Tables, **A7**, 233 (1970))

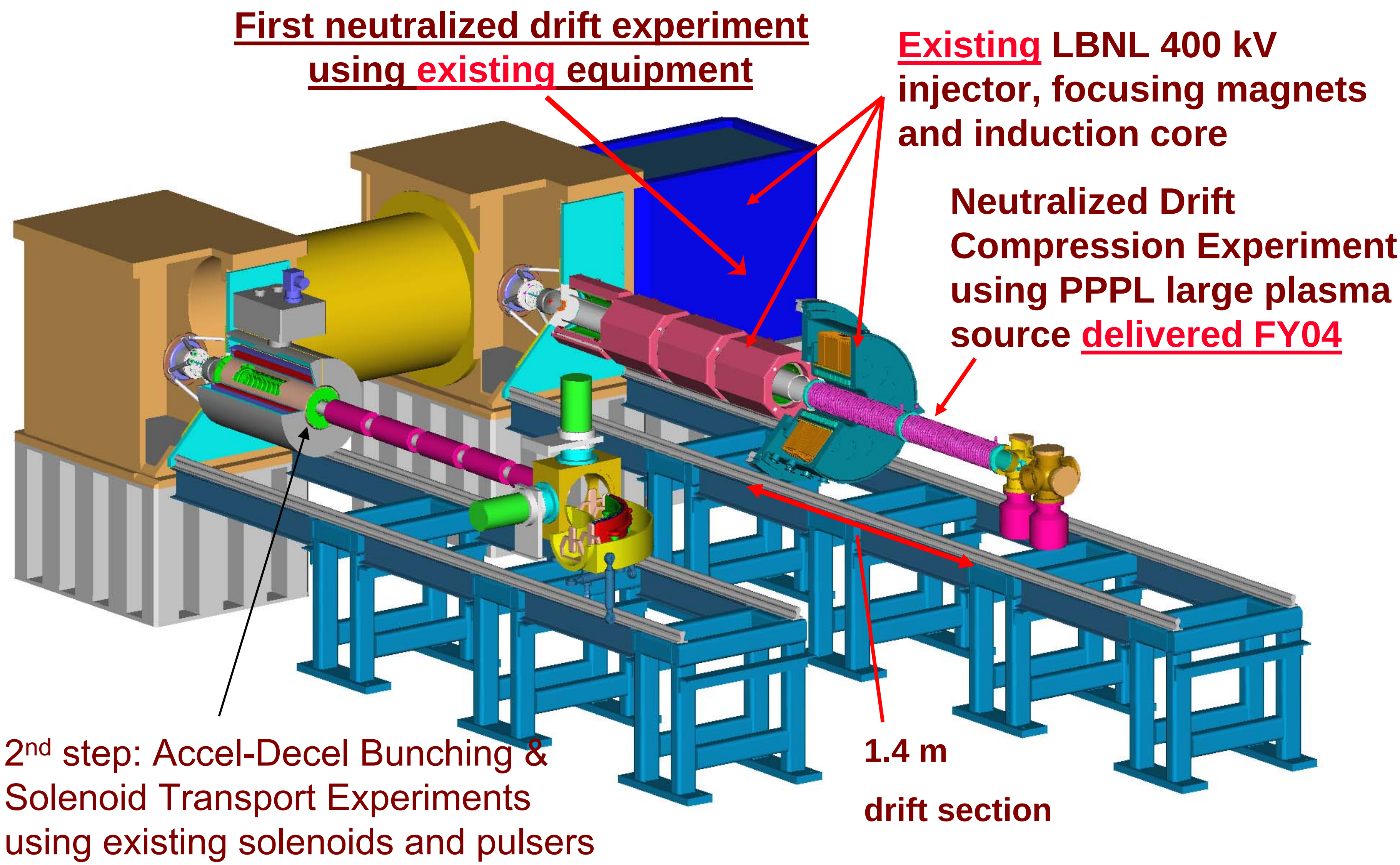
Simulations of first proposed experiment (NDCX-I) show large compression of tailored-velocity ion beams *inside a plasma column* (Welch, Henestroza, Yu 3-11-04)



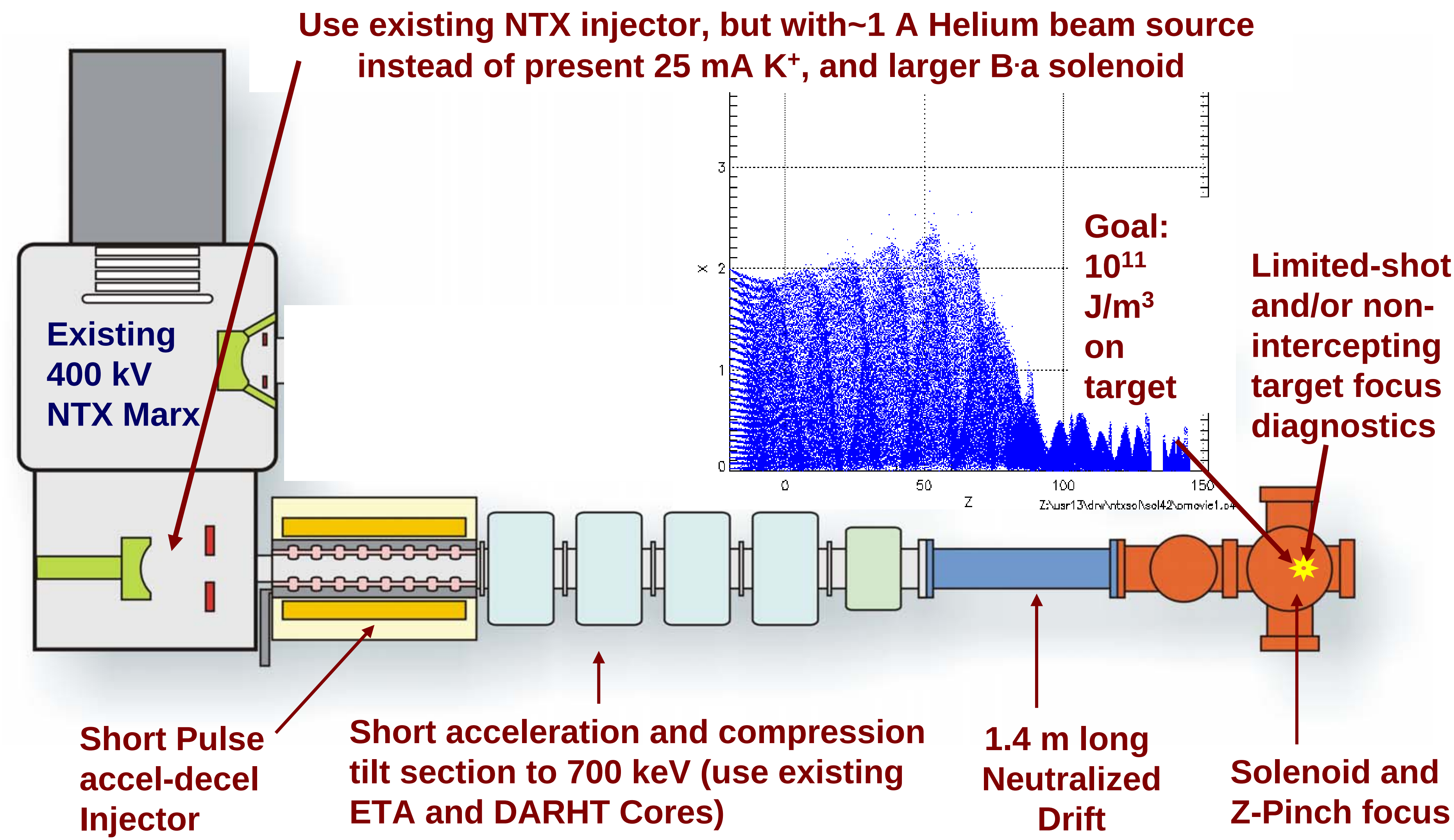
←**Ramped 220-390 keV heavy ion beam**

- **Axial compression 120 X**
- **Radial compression to focal spot radius < 1 mm**
- ***Beam intensity on target increases by 50,000 X*.**

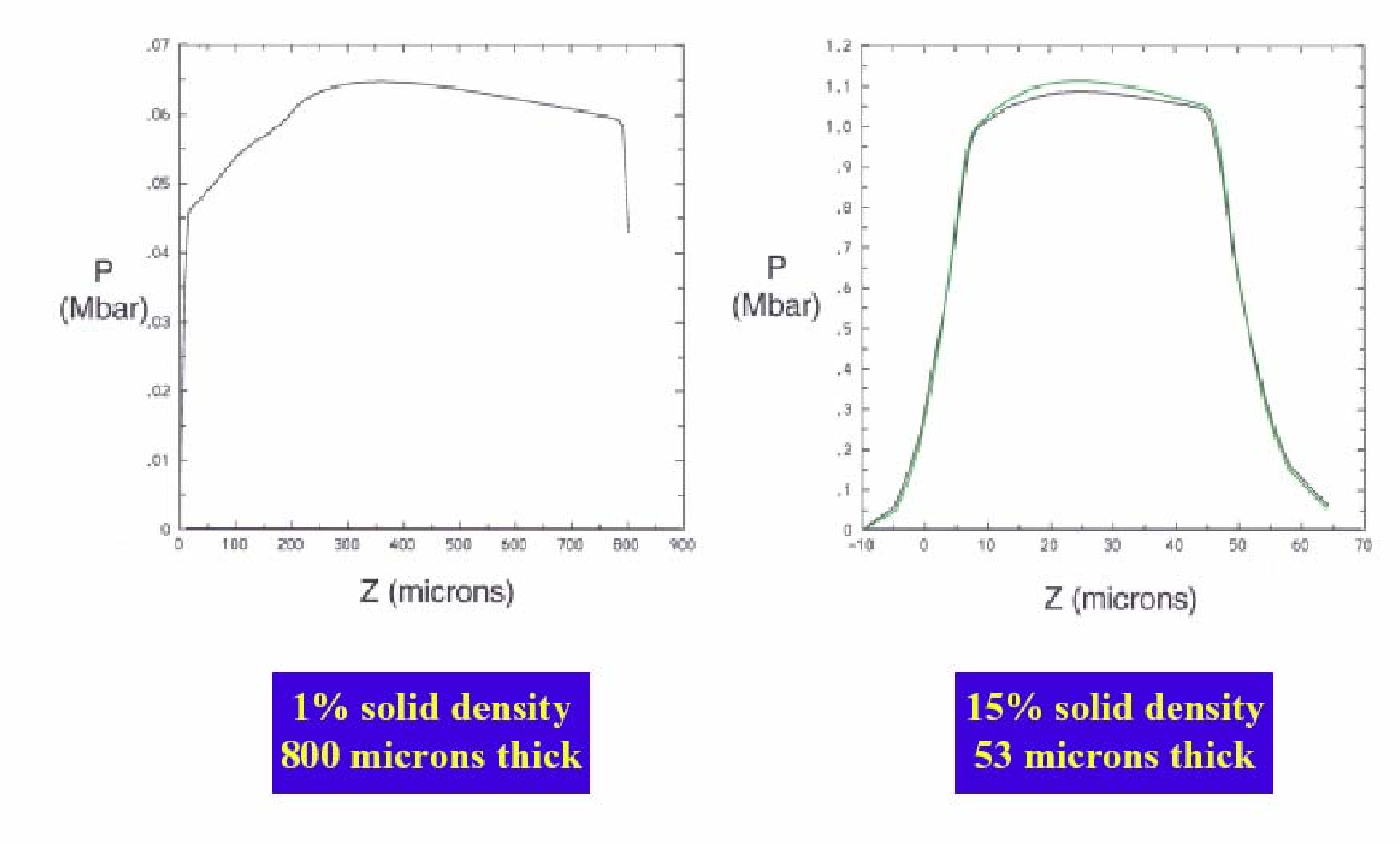
First experiments (~FY06) to assess physics limits of neutralized ion beam compression to short pulses (NDCX-I, before upgrade to NDCX-II)



FY09 milestone: Integrated beam and target experiments reaching HEDP threshold of 10^{11} J/m^3 (NDCX-II)



Using a low density target with the “2015” machine results in more uniformity, but less energy density

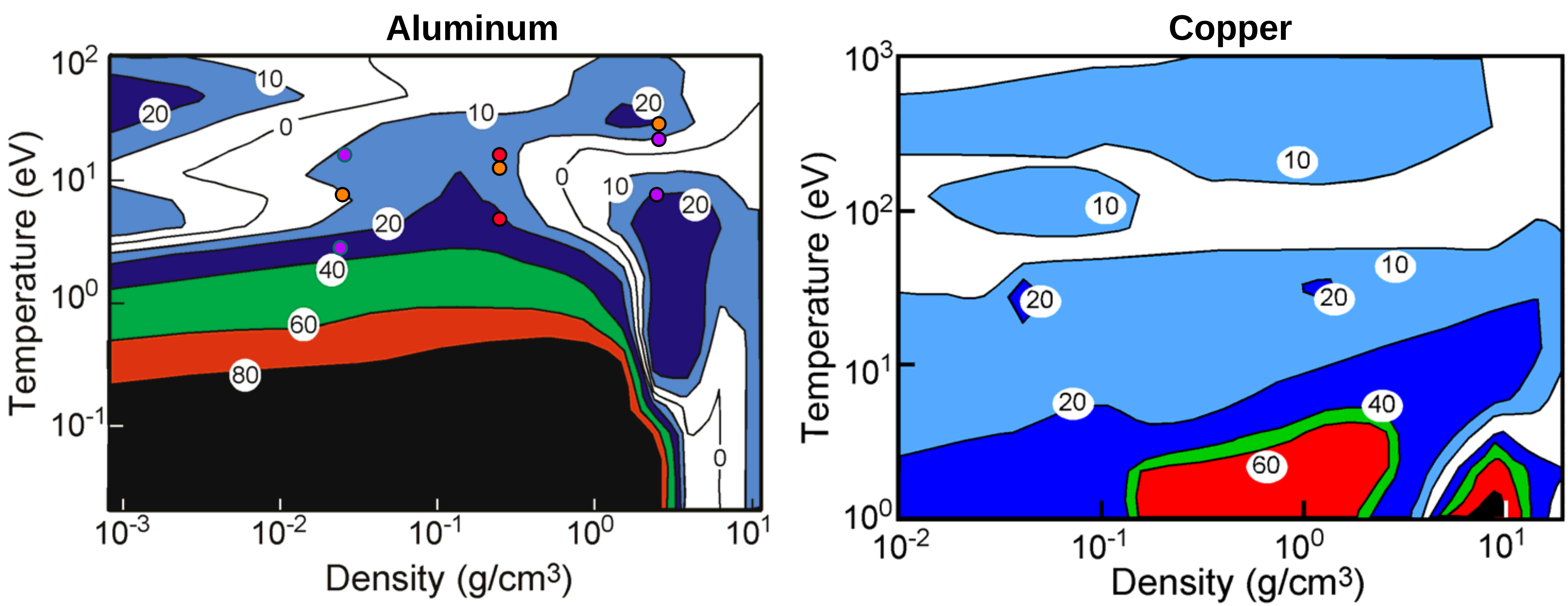


(slide courtesy D. Callahan and M. Tabak, LLNL)

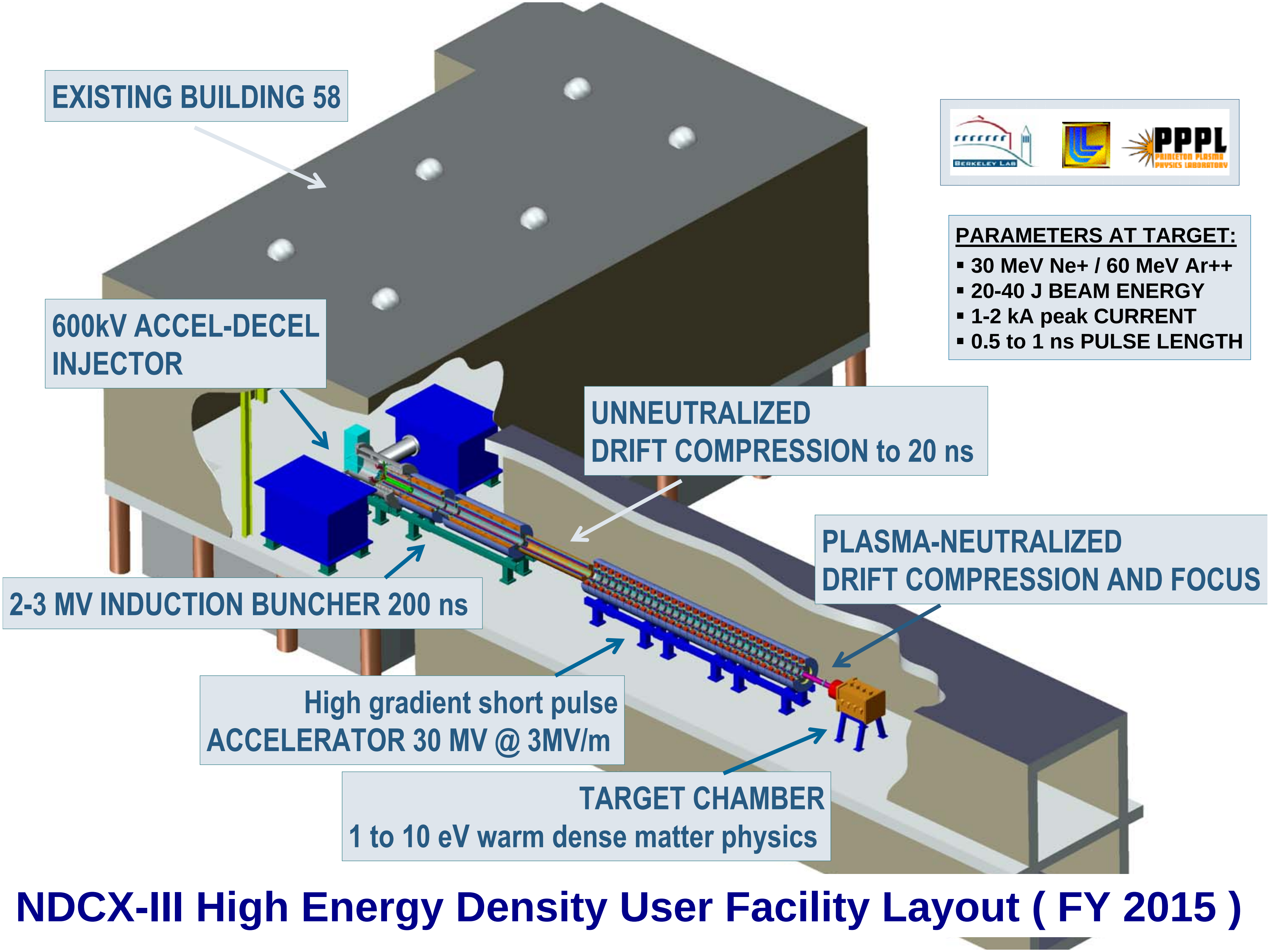
In Warm Dense Matter regime large errors exist even for most studied materials

(slide courtesy R. Lee, LLNL)

Contours of % differences in pressure



- EOS Differences > 80% are common
- Measurements are *essential* for guidance
- Where there is data the models agree!!
  - Data is along the Hugoniot - single shock ρ-T-P response curve



PARAMETERS AT TARGET:

- 30 MeV Ne+ / 60 MeV Ar++
- 20-40 J BEAM ENERGY
- 1-2 kA peak CURRENT
- 0.5 to 1 ns PULSE LENGTH

NDCX-III High Energy Density User Facility Layout (FY 2015)

Opportunities for Interagency Cooperation

With BES (SNS), with HEP (RHIC), and with NNSA (PSR) and in common issues of data, mitigation, and diagnostics for electron cloud effects.

With all agencies (e.g., BES, HEP, NNSA) sponsoring programs using intense accelerators that would benefit from joint development of advanced computational tools for electron cloud effects, beam halo production and associated losses.

With NNSA-sponsored electron beam radiography programs that would benefit from comparisons of equation of state and constitutive properties data for targets heated isochorically by particle beams.

With HEP for Plasma Wakefield Energy Doubler for a Linear Collider, on some common physics areas in compression and focusing limits with plasma lens and particle energy spreads.

Backup slides

Conclusion

Scientific campaigns in high brightness transport, compression, focusing, advanced computational tools, and beam-target interaction address the top-level scientific question central to both HEDP and inertial fusion energy (IFE):

How can heavy ion beams be compressed to the high intensities required for creating high energy density matter?

Understanding how beams can be compressed to 10^{11} J/m^3 (HEDP threshold) is a compelling intermediate step towards 10^{13}J/m^3 needed for IFE.

The new 10 year plan would meet the OMB/OFES 10-Year Measure for IFE/HEDP: ***"With the help of experimentally validated theoretical and computer models, determine the physics limits that constrain the use of IFE drivers in future key integrated experiments needed to resolve the scientific issues for inertial fusion energy and high energy density physics".***

Synergy with other HEP funded accelerator research (laser-based wake-field—short pulse xrays for diagnostsics

Example parameters: Ne^{+1} beam

Ne: Z=10, A=20.17, E_{min}=4.4 MeV, E_{center}=11.7 MeV, E_{max}=19 MeV
Δz_{min} = 40 μ

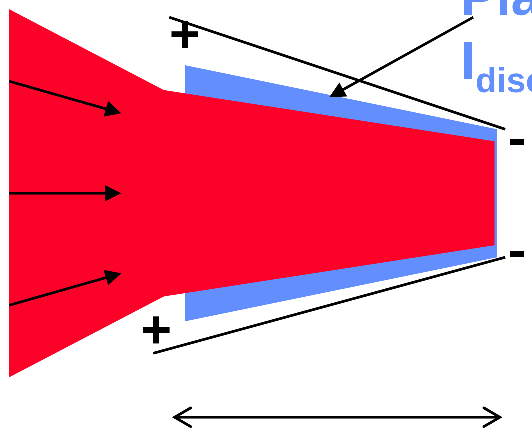
ρ(g/cm^3)(%solid)	0.027 (1%)			0.27 (10%)			2.7 (100%)		
Foil length (μ)	700			70			7		
kT (eV)	3.5	7.9	15.	4.5	15	20	7.2	32	38
Z*	1.5	2.8	3.4	1.3	2.8	3.3	1.1	2.8	3.4
$\Gamma_{ii}=Z^{*2}e^2n_i^{1/3}/kT$	0.77	1.4	0.93	0.99	1.4	1.45	0.95	1.4	1.7
$N_{ions}/(r_{spot}/1mm)^2$ $/10^{12}$	2.2	6.4	22	2.2	14	22	2.2	22	30
Δt (ns)	56	33	18	2.6	1.0	0.8	0.03	0.01	.008
U (J/m^3)/10^{11}	.021	.073	0.21	0.21	1.27	2.1	2.1	21	28

(Eq. of state, Z*: Zeldovich and Raizer model from R.J. Harrach and F. J. Rogers, J. Appl. Phys. **52**, 5592, (1981).)

"Adiabatic plasma lens" can be used as a final focusing optic with large velocity acceptance

Plasma discharge:
$I_{discharge}$ ~ 100 kA

Beam coming from final solenoid



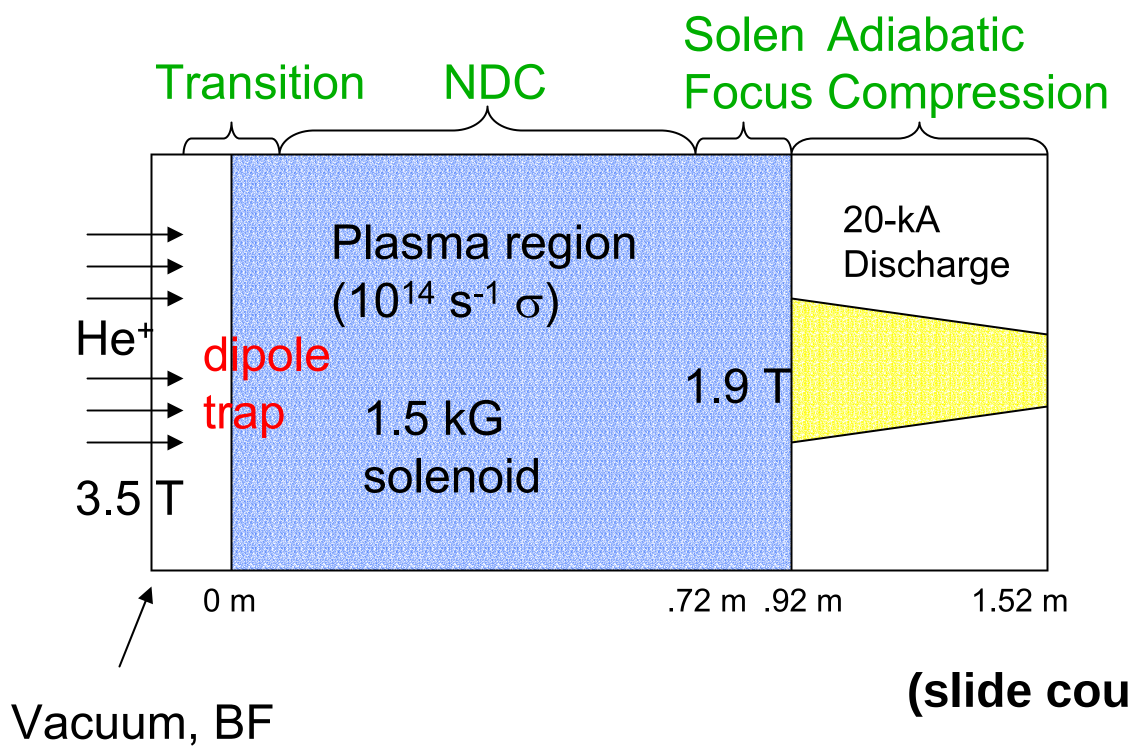
B_θ from discharge current x v_z from beam provides focusing force

Length of lens
>~ 1 "betatron" or particle oscillation length, so particles are "funneled" to a focus

Velocity spreads $\Delta v/v$ ~ 1 are transmitted;
Ultimate spot size determined by balance between focusing force and beam emittance

Phase 2: 10 A, 100-ns He beam at end of accelerator

Compressed from 1-A 1-μs beam in accel-decel injector
ε=1.2π-mm-mrad, r=2cm, .75 J
60-cm long adiabatic discharge channel (20 kA); 10 mm to 1 mm radius
67% energy tilt from 500-1000 keV in 100 ns
Need to compress 100x and focus to 1-mm spot to achieve "HEDP"



(slide courtesy D. Welch)

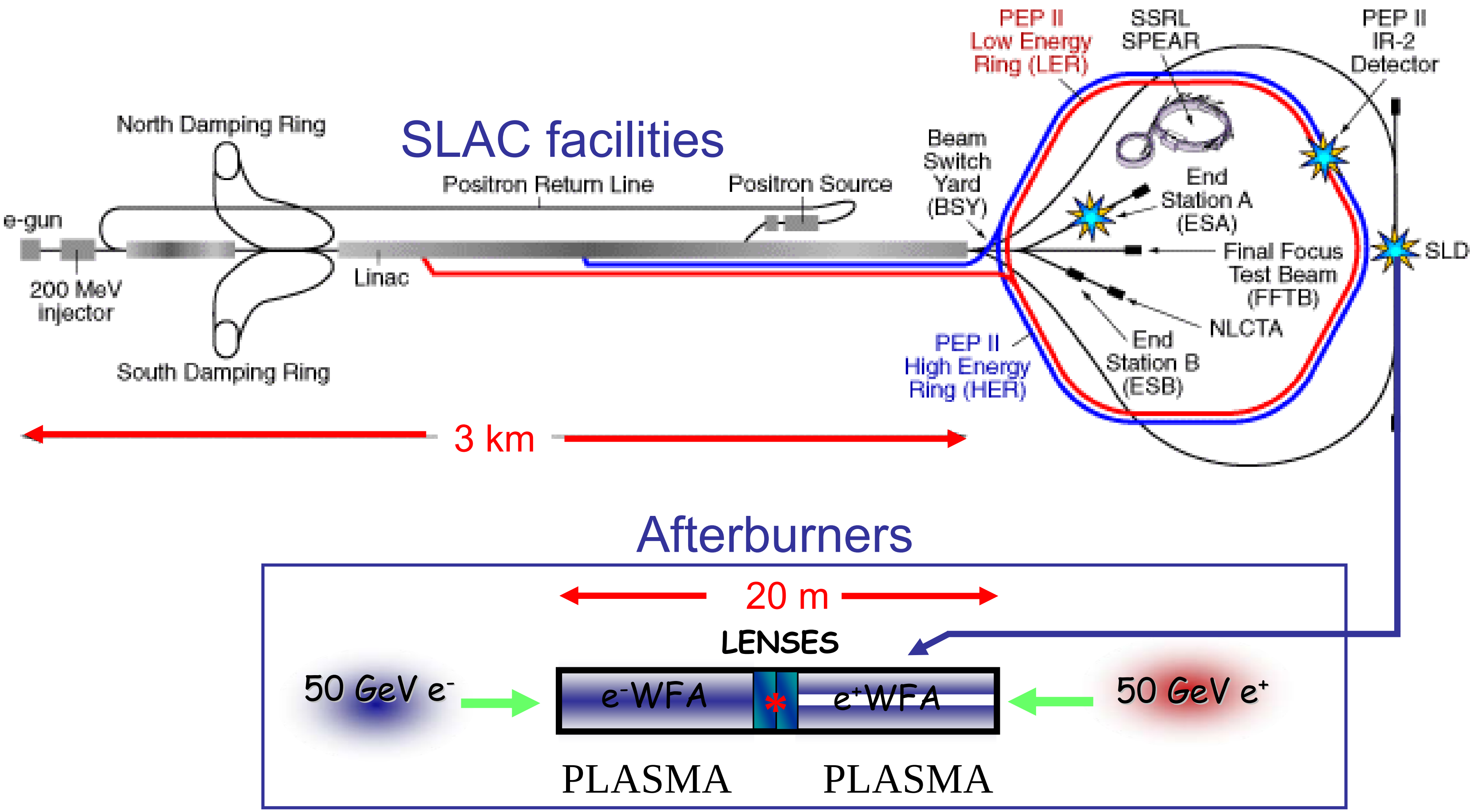
Thrust Area 5:

High Energy Density Science with Ultra-Relativistic Electron Beams

For Chan Joshi

Compelling Question :
High Energy Density Science with Ultrarelativistic Electron Beams:

How can the ultra high electric fields in a beam-driven plasma wakefield be harnessed and sufficiently controlled to accelerate and focus high-quality,high-energy beams in compact devices?


SLAC facilities
North Damping Ring
South Damping Ring
e-gun
200 MeV injector
Linac
Positron Return Line
Positron Source
Beam Switch Yard (BSY)
PEP II Low Energy Ring (LER)
SSRL SPEAR
PEP II IR-2 Detector
End Station A (ESA)
Final Focus Test Beam (FFTB)
SLD
NLCTA
End Station B (ESB)
PEP II High Energy Ring (HER)
3 km
Afterburners
20 m
LENSES
50 GeV e⁻
e⁻WFA
e⁺WFA
50 GeV e⁺
PLASMA
PLASMA

Drive Beam Energy	50 GeV
Number of Particles in Drive Beam	3e10
Trailing Beam Energy	50 GeV
Number of Particles in Trailing Beam	1e10
R.M.S, Bunch Length of Drive Beam	45 microns
R.M.S. Bunch Length of Trailing Beam	10 microns
Spacing Between Bunches	0-150 micron
R.M.S. Spot Size of the Bunches	1-3 microns
Plasma Density	2e16 cm-3
Average gradient	16 GeV/m
Transformer ratio	1-1.2
Energy Spread	5-10%
Length of Accelerating Sections	3 m

Table 1: A Non-Optimized set of beam and Plasma Parameters for a 100 GeV Afterburner

Scientific Milestones and Objectives

1) Can appropriately shaped (drive and trailing) electron and positron bunches with a variable spacing and the necessary charge be generated to excite the wakefieid and extract the energy from it?
2) Can one demonsrate relatively efficient beam loading of the wake and obtain a reasonable energy spread of the trailing beam?
3) Can transformer ratios of greater than 2 be obtained by shaping the drive beam?
   This may make it possible to add more than twice the drive beam energy to the trailing beam

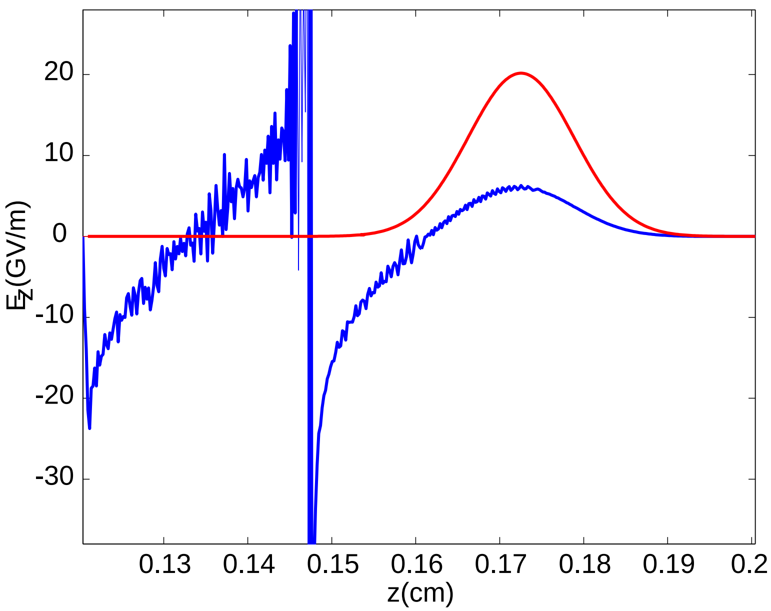
Scientific Milestones and Objectives

4) Production of 1-10m homog. (and tapered) Plasmas
5) Stable beam propagation from 10cm-10m of high-density plasma w/o hosing/erosion
6) Compatible integration of plasma into a beam dump/detector
7) Hollow channel accel. of positron beam
8) Positron beam accel. on an electron wake
9) Matched beam propagation
10) Hi demagnification plasma lenses
11) 1-to-1 computer modeling of 10m-scale expts.
12) Generation of intense X-rays and γ-rays via plasma wigglers
13) Production of ultra-low emittance beams for future X-ray FELs (as well as matching to plasma stages)

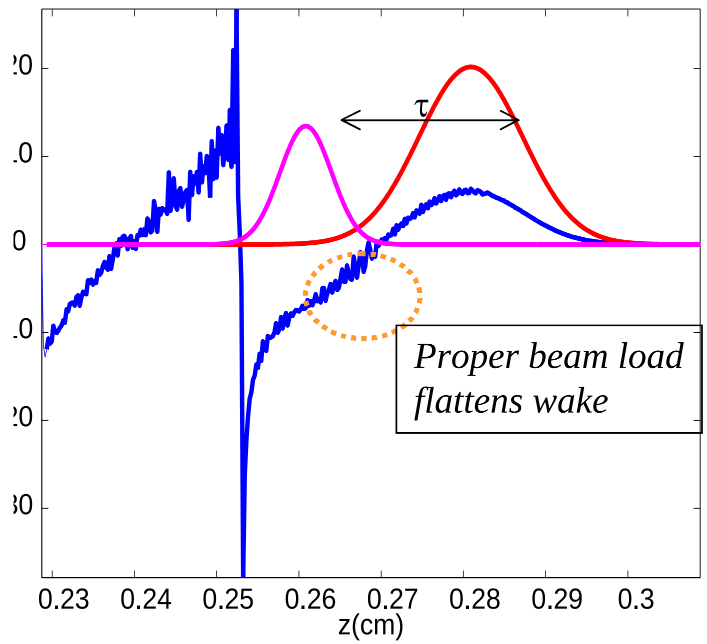
PIC Simulation of 2 bunch Afterburner Experiment

Hi beam quality requires specialized infrastructure of ORION beamline

(shorter 2nd bunch, precise phasing τ)



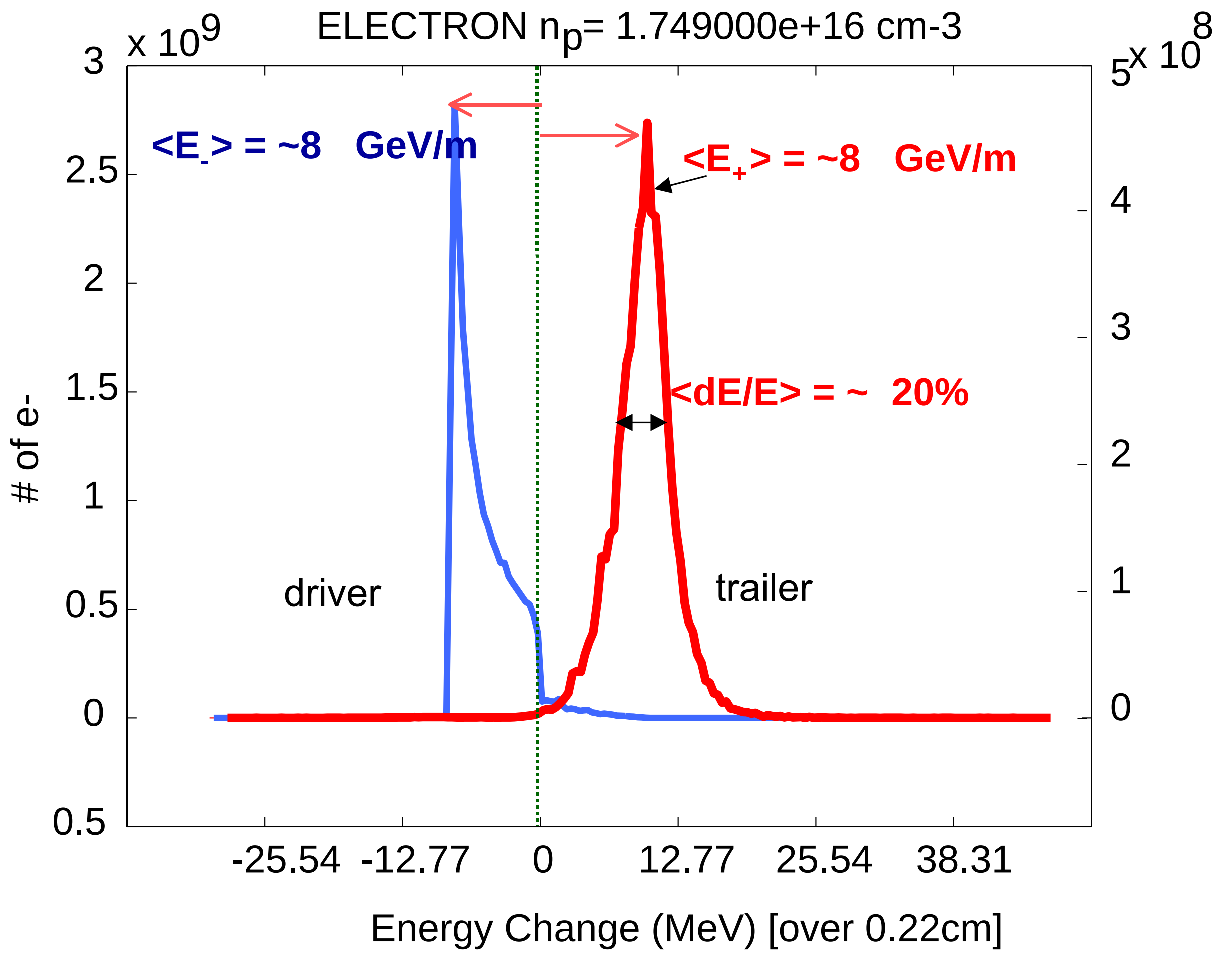
Driving bun ch only



Driving bun ch N=3 $\times 10^{10}$ σ_z=0.063mm

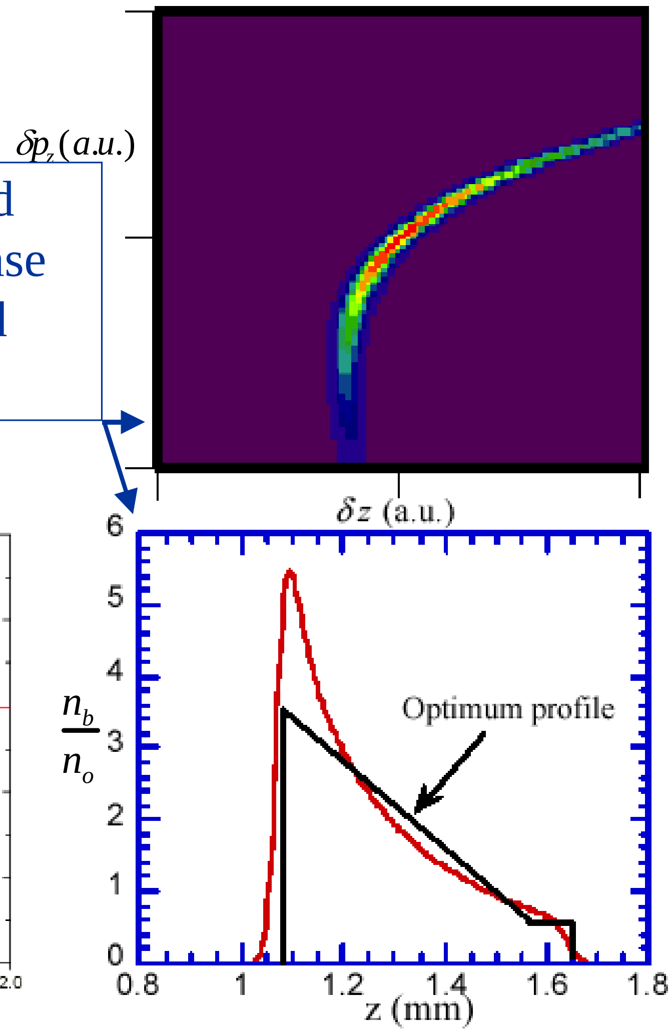
Trailing bunc h N^- =1 $\times 10^{10}$ σ_z(trailing) = σ_z/2

Energy distribution of driver & trailer

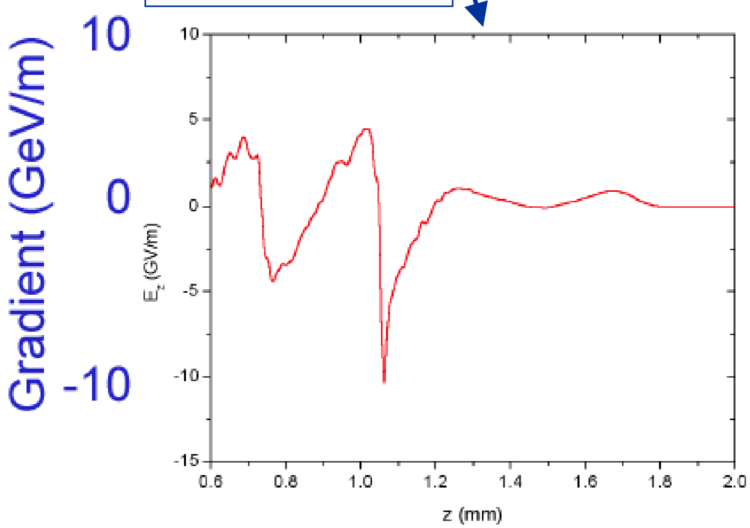


Research on bunch shaping can give hi Transformer Ratio

Simulated beam phase space and shape



Simulated Wake



Resource Requirements

1. Dedicated high energy beam line with beam compression for both electrons and positrons

   $10M

2. Science Program

   $5M/yr

Agency Cooperation

DoE-HEP – support plasma accel/focusing; accel. development
DOE-BES –e- and e+ pulse compression, radiation generation, emittance reduction
NSF—beam propagation physics, relativistic beam-plasma interactions

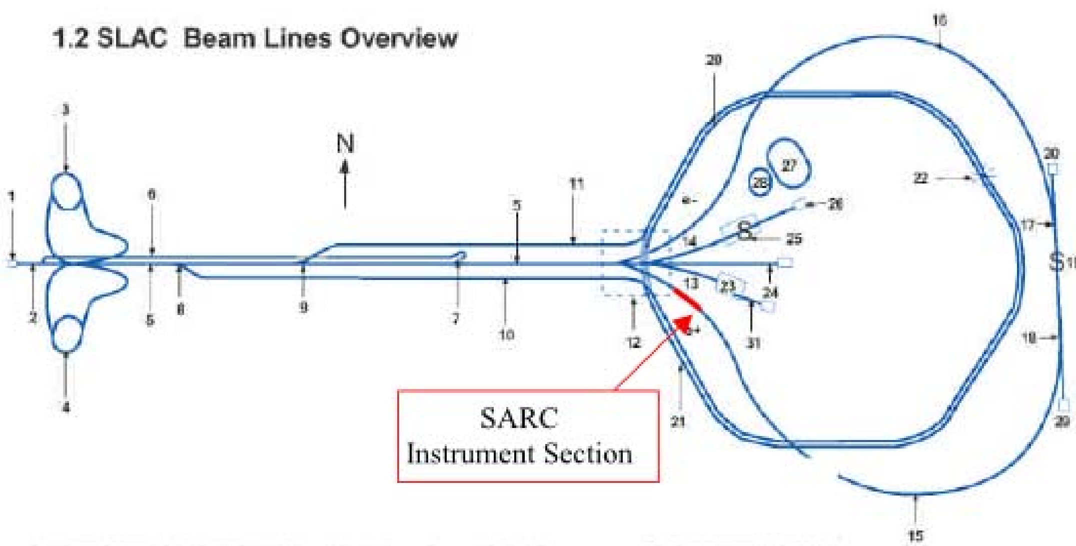
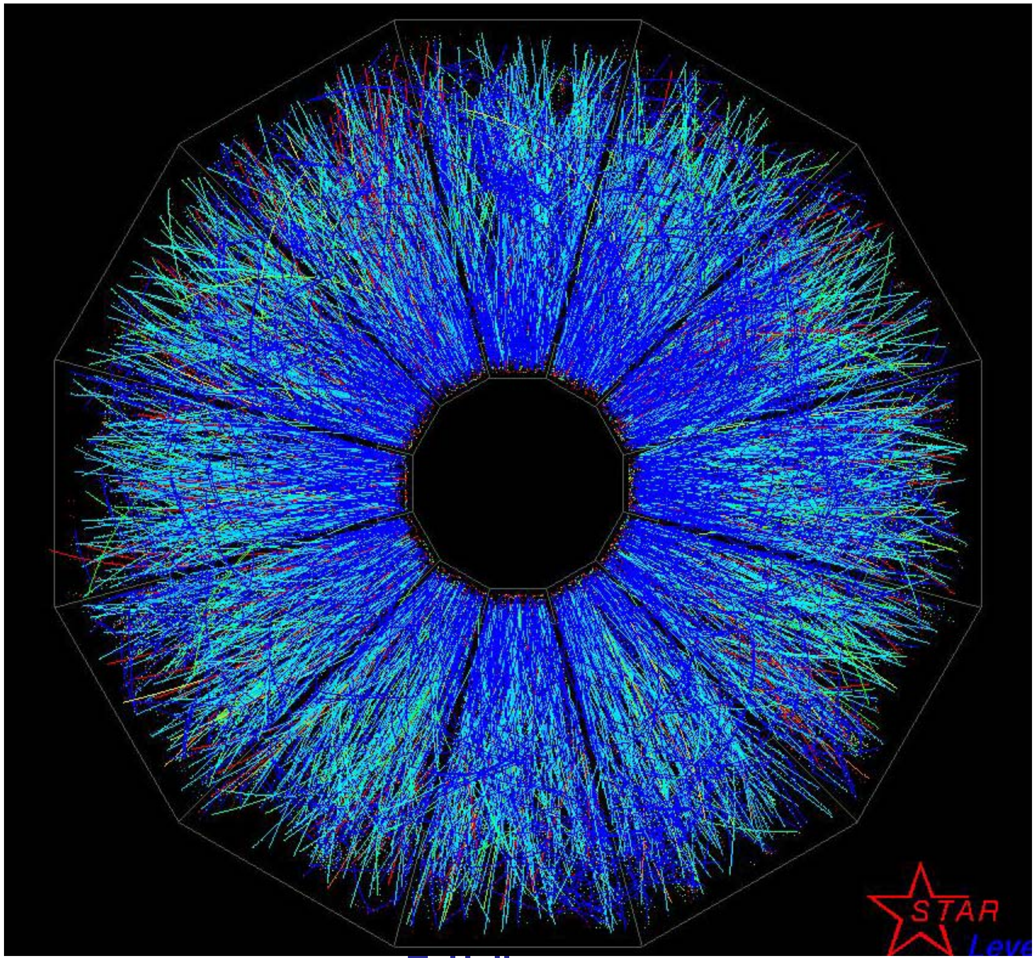


Figure 1. Location of the Instrument Section close to the beginning of the SARC

Courtesy P. Krejcik, P. Emma

The Tools Needed to Explore the High Energy Density Frontier at RHIC II



T. Hallman

HEDP Conference Gaithersburg, MD

May 24-26, 2004

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Office of Science U.S. DEPARTMENT OF ENERGY

Compelling questions

- *What is the nature of matter at exceedingly high density and temperature?*

- *Does the quark gluon plasma exhibit any of the properties of a classical plasma?*

The Ongoing Scientific Journey at RHIC

Search and discovery → Exploring new states of matter

Do we have "Matter" at high energy density?

- Strong collective interaction; local kinetic equilibrium…
  Large volume compared with mean free path? } .... **Yes**

Is it quarks and gluons?

- Temperature and energy density well above critical values? .... **Yes**
- Strong collective interaction at very early times? .... **Very likely yes**
- Color screening in dense phase? .... **First results coming soon**
- Opaque to jets? .... **Yes**

Is there a QCD phase transition?

- Chiral symmetry restored (shifted ρ mass)?
- Lattice QCD predictions for the equation of state (latent heat/deconfinement)?
- Fluctuations near phase boundary?

•Nature of a possible saturated initial-state gluon distribution

Like all good science, one advance leads to even more interesting, fundamental scientific questions

Scientific objectives:

- Heavy quark probes
  - High mass $\rightarrow$ high E to produce (made at 1st step in collision)
  - Screening properties via (c-anticharm) bound states
  - Do the heavy quarks thermalize? Lose energy?
  - *higher luminosity $\rightarrow$ sufficient statistics of rare, heavy quarks*
  - *lattice calculation under relevant conditions*
- Initial quark gluon plasma temperature
  - *detector upgrade for background rejection*
  - *lattice, hydro simulations (with relevant ρ, coupling)*
- Characterize this new kind of plasma
  - radiation rate, conductivity, collision frequency
  - *Need rare probes, including tagged jets*
  - *detector & accelerator improvements; simulations*
- Consistent theoretical picture of
  - quark gluon plasma, heavy ion collision to connect with data
  - *Need large scale computational resources for numerical simulation*

How to get there?

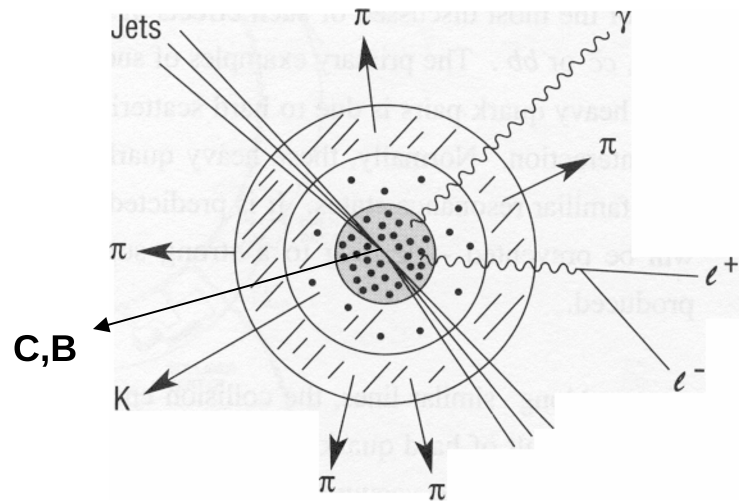
- Experimental side – upgrade facility (~2009-2015)
  - increase RHIC luminosity by ~40
  - by electron cooling of heavy ion beams
- Capabilities of large detectors (2 steps between now & 2015)
  - technology for rare features in high muliplicity events
  - secondary decay vertices
  - background rejection
  - triggering, readout capabilities
  - data analysis infrastructure (already write 0.5 pB/year)
- Theory progress (over next 5-10 years)
  - Large scale computing resources
  - lattice QCD, hydrodynamic & transport simulations
  - Personnel to develop new approaches

What's Needed?

To exploit this opportunity, the future RHIC HI program, beyond the present exploratory phase, is driven by the need for sensitivity to rare processes.

Not because the QGP, etc. are rare phenomena in these collisions, but because signals that can reveal the details of early-time phenomena are rare processes.

High p_T hadrons
Heavy quarks (bound & unbound)
Direct photons, electrons
Direct γ + jet, di-jets



A+A Species scan
p+p Energy scan
p+A

Physics Beyond Reach of Current RHIC Program

Provide key measurements so far inaccessible at RHIC in three broad areas:

- Comprehensive study of QCD at high T with heavy ion, p-nucleus, and pp
  - high p_T phenomena (identified particle, p_T>20 GeV/c and γ-jet)
  - electron pair continuum (low masses to Drell-Yan)
  - heavy flavor production (c- and b-physics)
  - charmonium spectroscopy (J/ψ, ψ' , χ_c and Υ(1s),Υ(2s),Υ(3s))

requires highest AA luminosity

- Extended exploration of the spin structure of the nucleon
  - gluon spin structure (ΔG/G) with heavy flavor and g-jet correlations
  - quark spin structure (Δq/q) with W-production
  - Transversity

requires highest polarization and luminosity

- Exploration of the nucleon structure in nuclei
  - A-, p_T-, x-dependence of the parton structure of nuclei
  - gluon saturation and the color glass condensate at low x

Requires not only upgrade of RHIC luminosity
But also of the experiments
The needs have been studied over the last 2 years

Measurements foreseen in the PHENIX and STAR decadal plans

Extended machine & detector capability at RHIC

High P_t and Q^2:

- Direct photons to P_t > 15 GeV/c
- Photon-tagged jets…*jet tomography*
- Low x, high Q^2 in pA… *Probe color glass*

Rare probes:

- Open Charm and Beauty
- Many x1000 upsilons
- W production in AA, pA, pp

Very large unbiased event samples:

- Low mass lepton pairs… ρ mass spectrum } Direct EM radiation from plasma
- Low P_t Direct Photons } Direct EM radiation from plasma
- $\gamma\gamma$ interferometry…
- Disoriented Chiral Condensate; Strong parity violation

Most of these require data samples <u>per run</u> equivalent to 10/nb in Au-Au
RHIC will integrate ~ 10/nb up to 2010 at present (design) luminosity !

Long Term RHIC Operation and Upgrade Plans

2004 2005 2006 2007 2008 2009 2010 2011 2012 2013 2014 2015 2016 2017 2018

RHIC operation at and beyond design luminosity

eRHIC
e-ion collider

RHIC II 40x design luminosity for Au-Au via electron cooling

RHIC baseline program
- Au-Au ~ 1 nb^{-1} at 200 GeV
- Species scan at 200 GeV
- Au-Au energy scan
- Polarized protons $\geq$ 150 nb^{-1}

Completion of
- BRAHMS & PHOBOS

Studies of dense nuclear matter
with rare probes: jet tomography, open flavor,
J/ψ, ψ', χc, $\Upsilon(1s)$, $\Upsilon(2s)$, $\Upsilon(3s)$
Polarized protons at 500 GeV
p-A physics

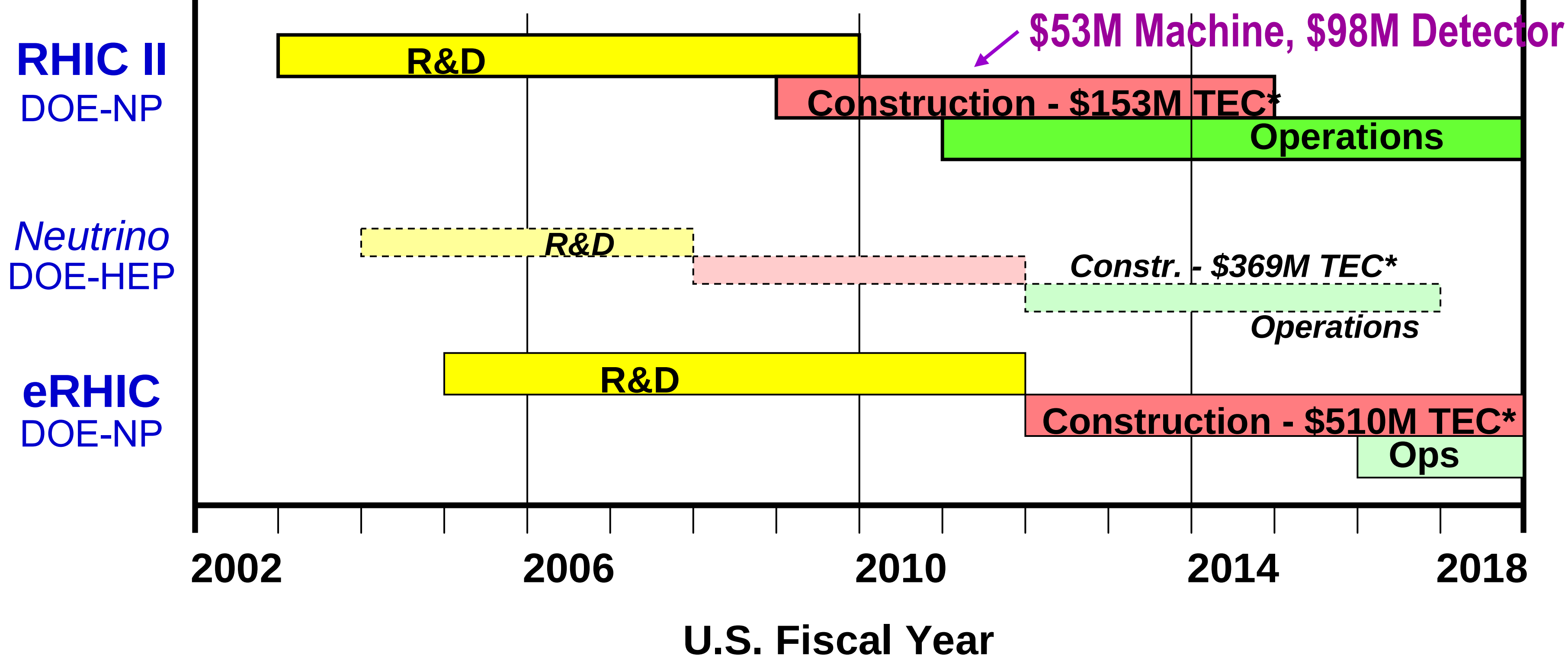
Near & medium term detector upgrades
of PHENIX and STAR
Proposals submitted or in preparation

New eRHIC experiment

Long term upgrades
of PHENIX and STAR
related to RHIC II

new RHIC experiments ?

Future BNL Accelerator Facility Initiatives



Included as part of the DOE 20 year "roadmap"

Office of Science
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•These estimates in FY03 dollars and do not include escalation.

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Interagency opportunities?

- Currently DOE/NP & NSF cooperate in this area
  - RHIC operated by DOE/NP exclusively
- Collaboration on experimental & computational infrastructure
- Support for the people
- Opportunities?
  - Large scale simulation and data analysis computational resources

- Foster study of other HED questions which may be addressed by the same facilities
  - Accelerator physics relevant to HED???