Towards High-Energy Accelerators

Lepton-Photon 99

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- Overview
- High Gradient Acceleration
- Muon Colliders (and Neutrino Sources)
- Role of Plasma in Advanced Accelerators
- Very Large Hadron Colliders
- Perspectives

Overview

- Employing NLC technology for high energy (> 3TeV) colliders leads to extremely large machines and average powers. Some alternatives are being investigated:

  Compact linear colliders → high-gradient
  → problems:
  - New structures : fabrication, breakdown, wakefields,jitter,alignment
  - New power sources: efficiency, pulse length, coupling
  - New final focus : pinch effect, beamstrahlung, length,& backgrounds

  luminosity for sensible emittance

AND

  Muon colliders→muons → problems:
  - Production
  - Cooling
  - Collision
  - Decay

How is luminosity achieved?

Number of times bunches collide
e^+e^- :1; $\mu^+\mu^-$: 1000

Number of particles/bunch
$\mu^+\mu^-$: $2X10^{12}$ e^+e^- $4X10^9$

Av. power in beams

$$L = \frac{f_c N^2}{4\pi\sigma_x\sigma_y} \propto \frac{\bar{P} n_c N}{\sigma_x\sigma_y}$$

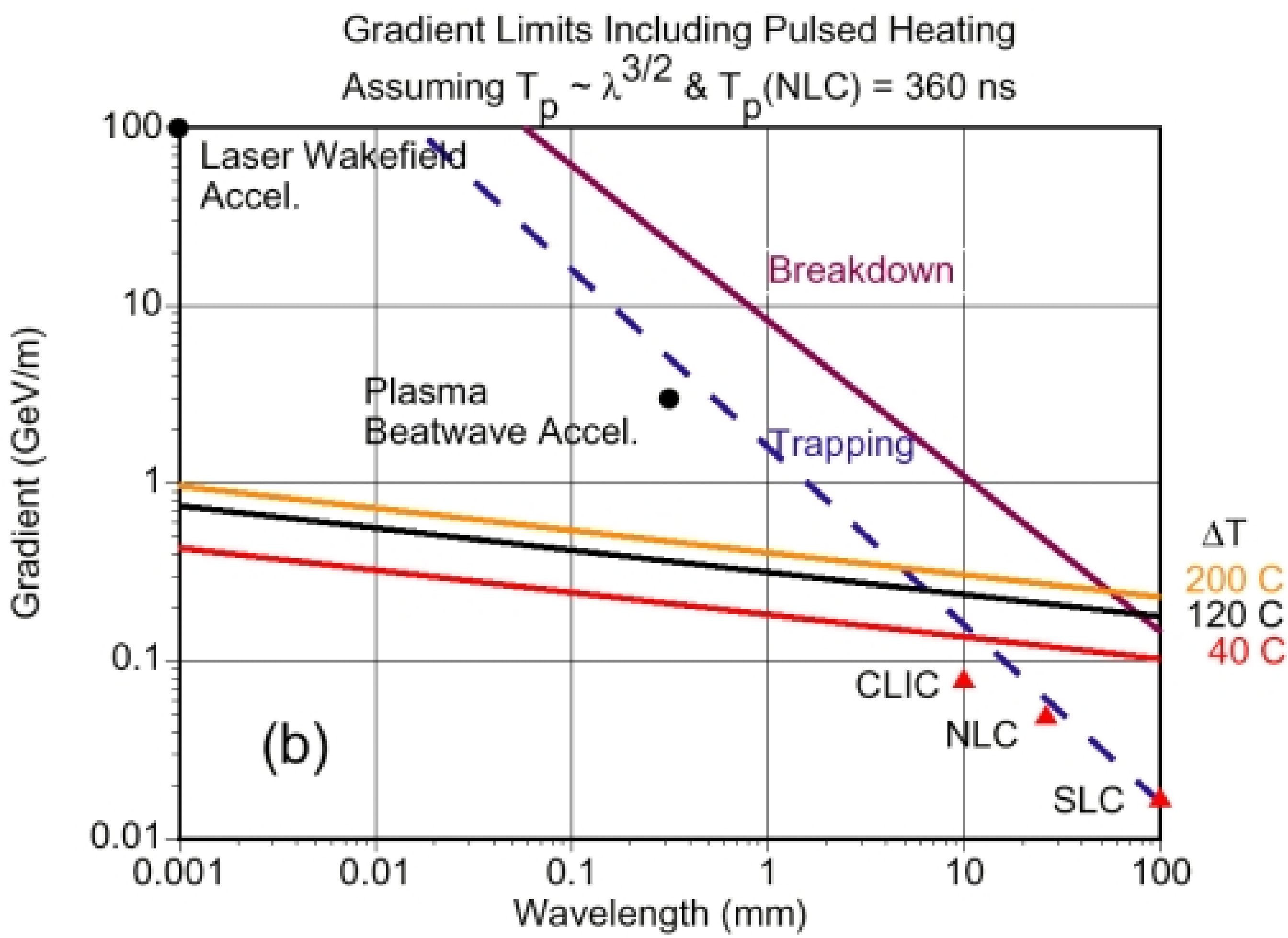
Spot size at IP
e^+e^- : 40nmX.6nm
$\mu^+\mu^-$: 3μmX3μm

	Beam power	Normalized emittance	β*
	MW	$\varepsilon_x/\varepsilon_y$(mm mrad)	mm
Muons 3TeV	14	50X50	3
CLIC 3TeV	11	.6/.01	8/.1
Matrix-linac	0.7 5TeV	.1/.1 IP compensation Beam combining	.15/.15

Note: IP compensation can improve all schemes.

A compact multi-TeV electron-positron collider might have

- New final focus:
  - neutral beam, $\gamma\gamma$ collisions, higher background
  - New focusing scheme: no chromatic correction, harmonic acceleration, multi-beam collisions/beam combining, dynamic focusing
- High Gradient and high frequency acceleration: 30GHz, 90GHz, THz, plasma, laser
  - Advanced Structure Concepts
    - Advanced materials
    - Composite structures
    - Novel configurations: Matrix accelerator, coupled cavities, disposable accelerators (plasmas)
    - Two-beam accelerators: CLIC, RKA



Pulse heating is thought to be the most serious limit to scaled solid-state structures

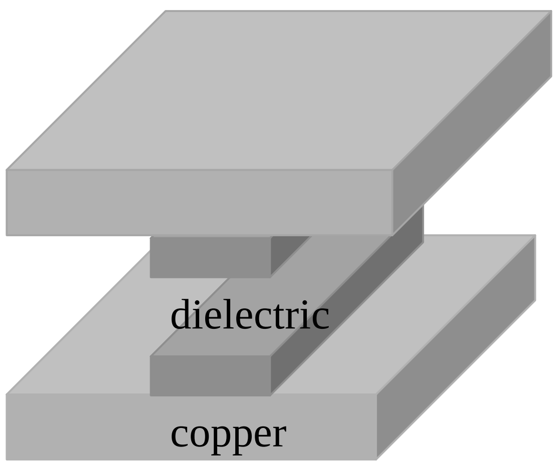
(Courtesy D. Whittum)

Composite Accelerator Structure

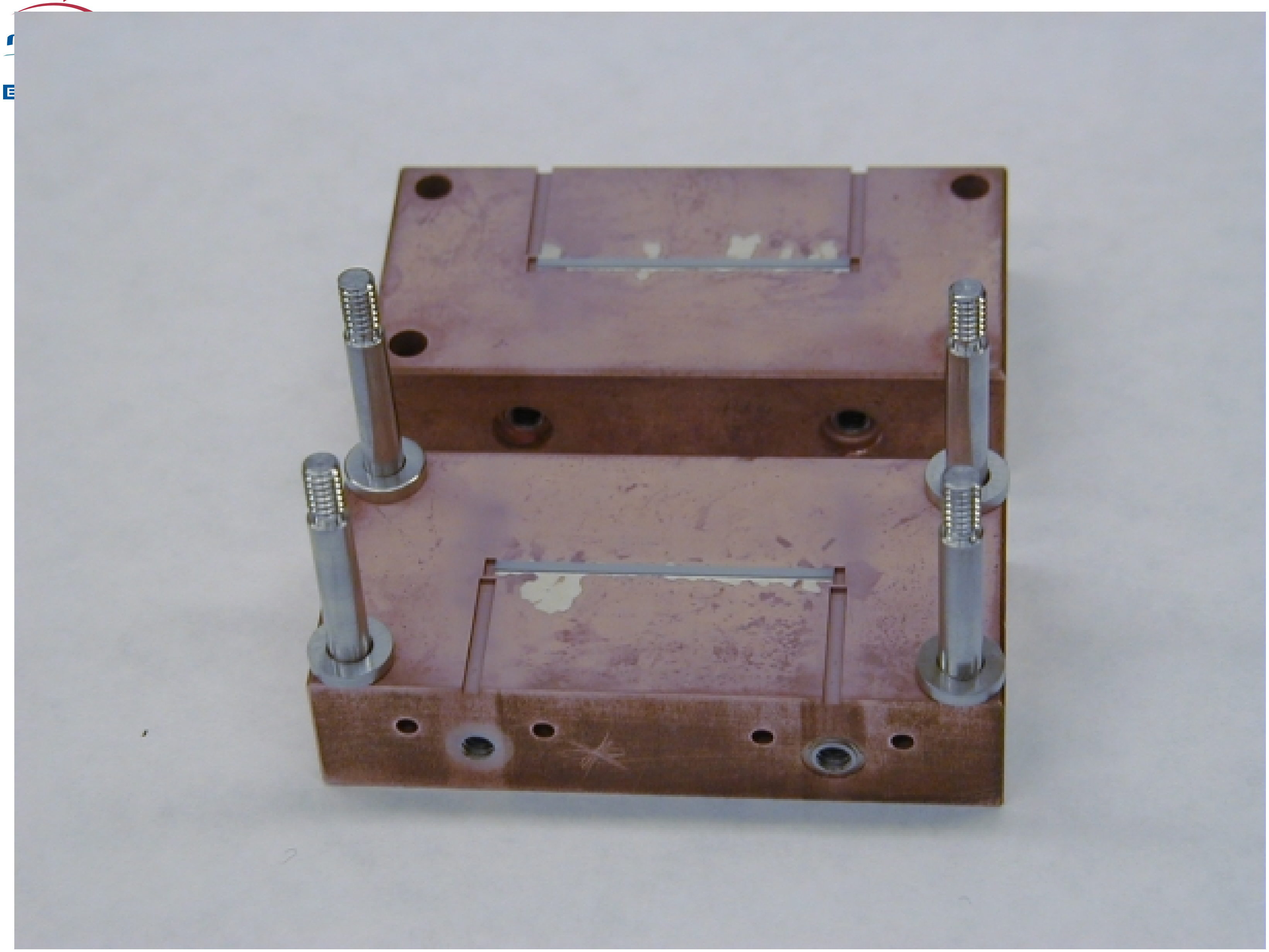
The traditional disk loaded waveguide, like those used at SLAC, use the periodic iris to slow down the phase velocity. The Composite Accelerator Structure (CAS) utilizes a dielectric to slow down the phase velocity to c. **M. Hill, et al., submitted to IEEE/MTT**.

Advantages:

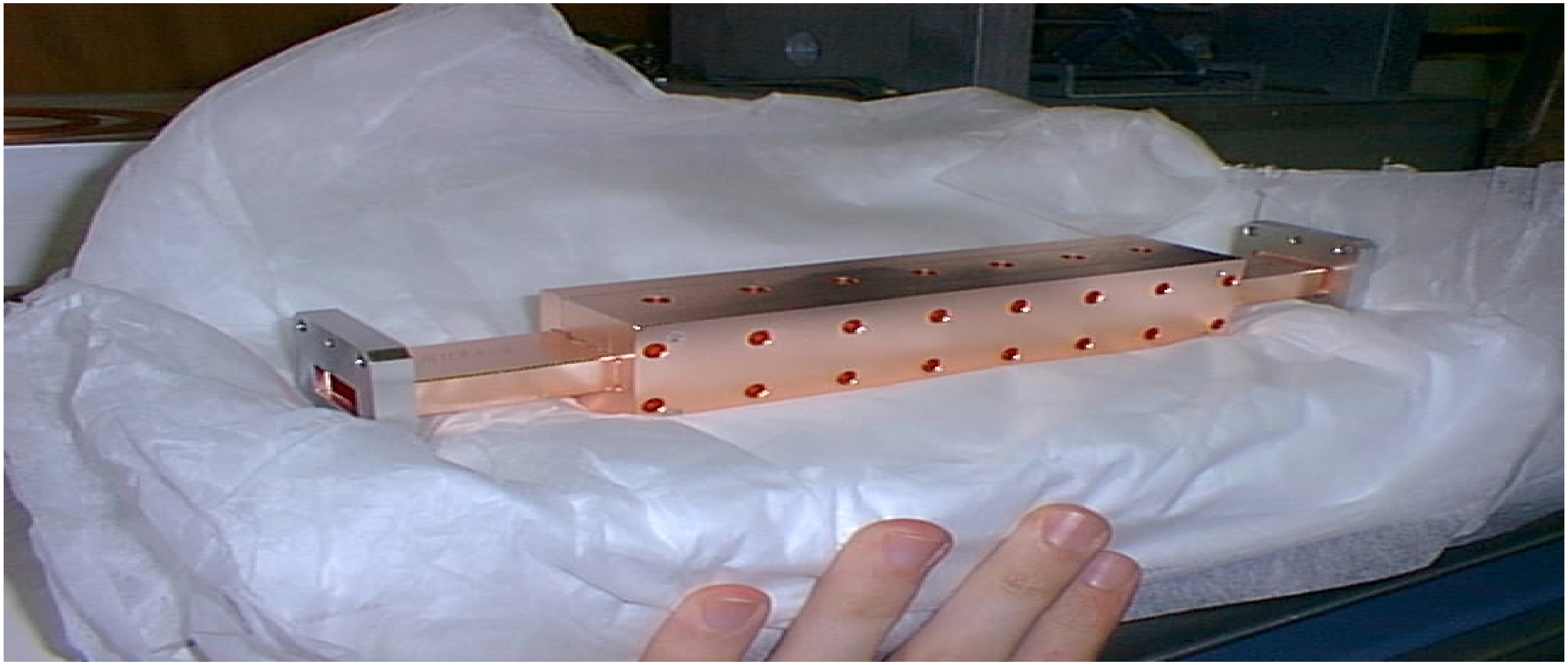
- The structure is simple to manufacture--no bonding, tolerant to machining errors.
- The planar geometry also makes tuning easier.
- CAS has inherently lower surface electric field.



- Powered by beam 300MeV, .4A, 100ns beam of NLCTA
- Bunched at 11.4GHz (8'th subharmonic).
- Beam was focused to ~0.3mm with full transmission
- Resonant interaction yields power of 8kW output from structure. Fields in excess of SLAC linac. M. Hill, et al., in preparation.

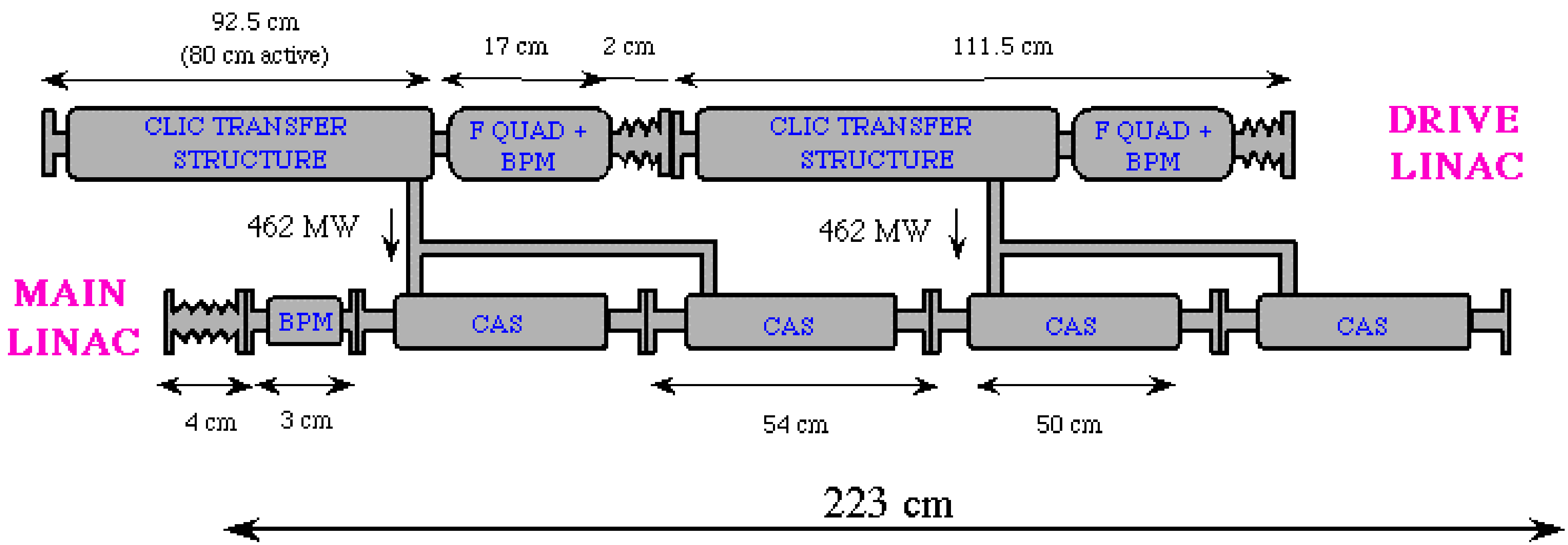


Matrix Linac: X-band prototype



TWO BEAM ACCELERATION (TBA)

(4 CAS + 2 TRS)/module
Drive beam with 1856 bunches of 17.5 nC/bunch



CLIC module layout
3 TeV

Muon Colliders

- Why muons?
  - Synchrotron radiation suppressed $\propto (1/m)^4$
  - Lepton energy advantage
  - Direct Higgs production $\propto m^2$
  - Potential for high resolution experiments (dp/p ~ .00003)
  - Can site 3TeV collider complex at existing laboratories
  - Can build in stages--
    - Neutrino storage ring
    - Higgs factory or intermediate energy collider
    - High energy collider

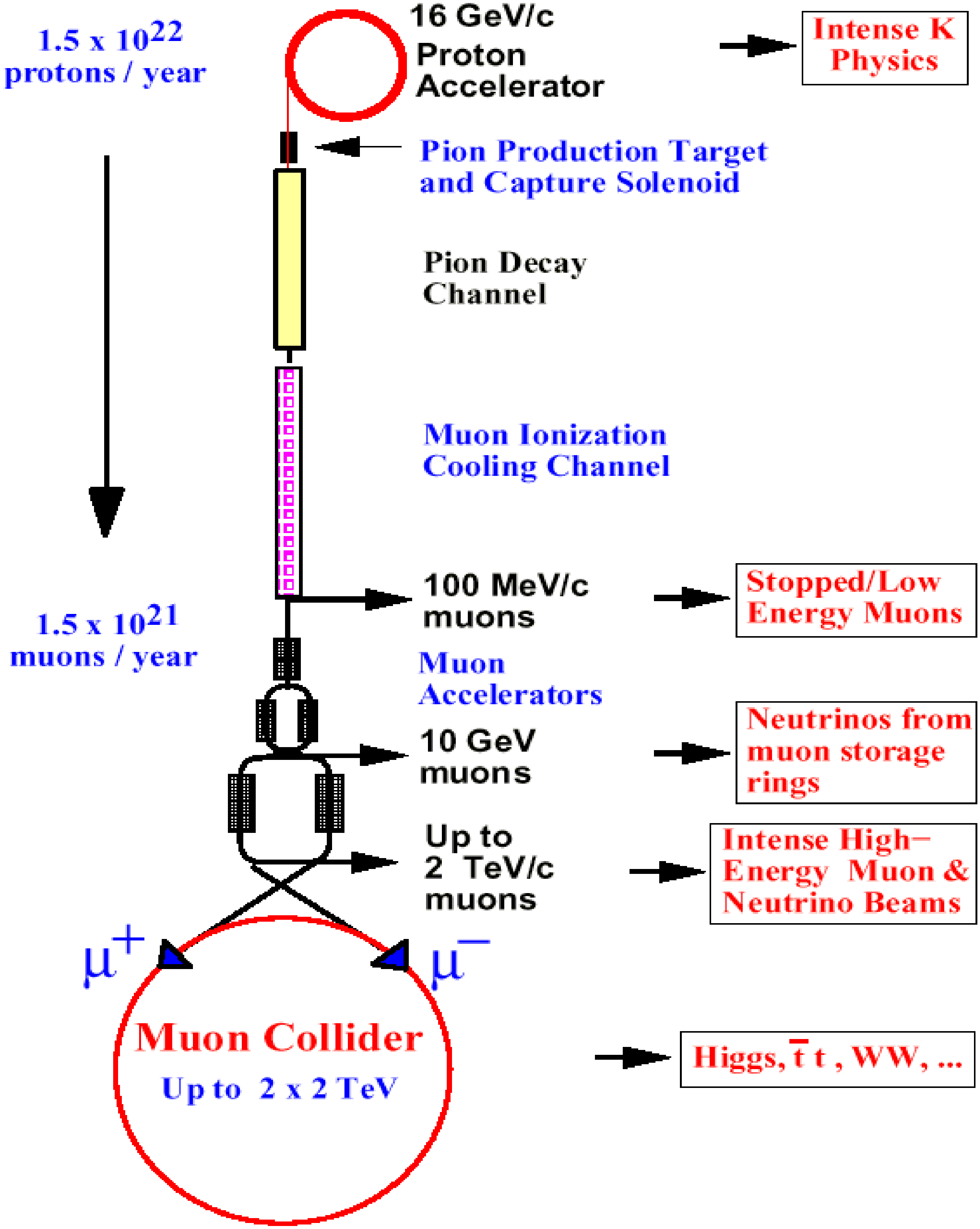
  - Refs and talks: http://www.cap.bnl.gov/mumu/, www.fnal.gov/projects/muon_coollider, links therein. Collaboration has roughly 120 members, 30-40 FTEs. R. Palmer, Spokesman.

Problems: Muons are produced in diffuse phase space and decay rapidly

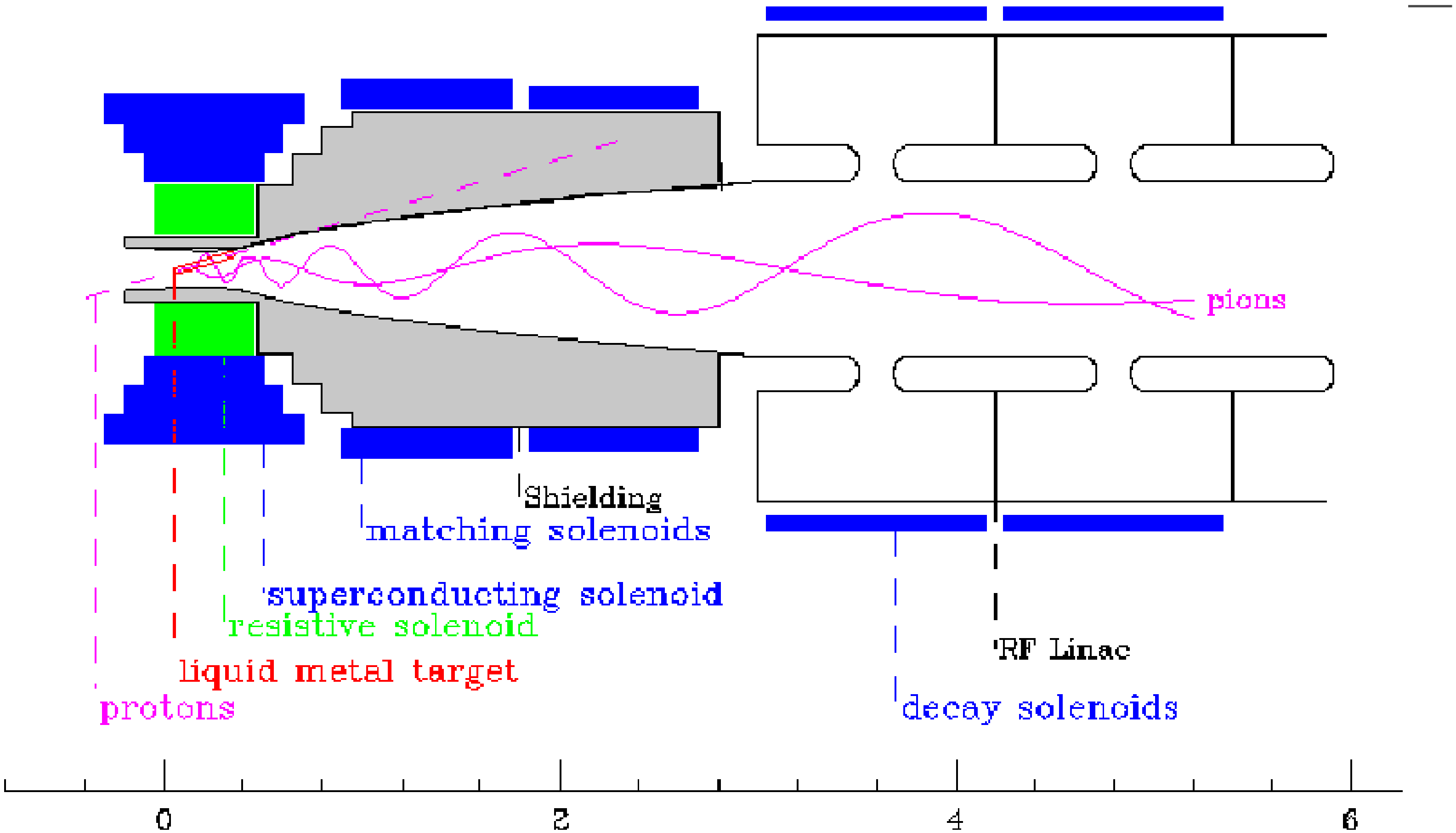
Requirements:

- High power (4MW) proton beam
- Efficient production/capture
- Rapid cooling and acceleration
- Isochronous collider ring with low beta insert, shielding in beam pipe from decay products
- Handling of background in detector
- Overcome neutrino radiation hazard at energies >3TeV CM
- Efficiency at high energy

Muon Collider Schematic



Target and Capture



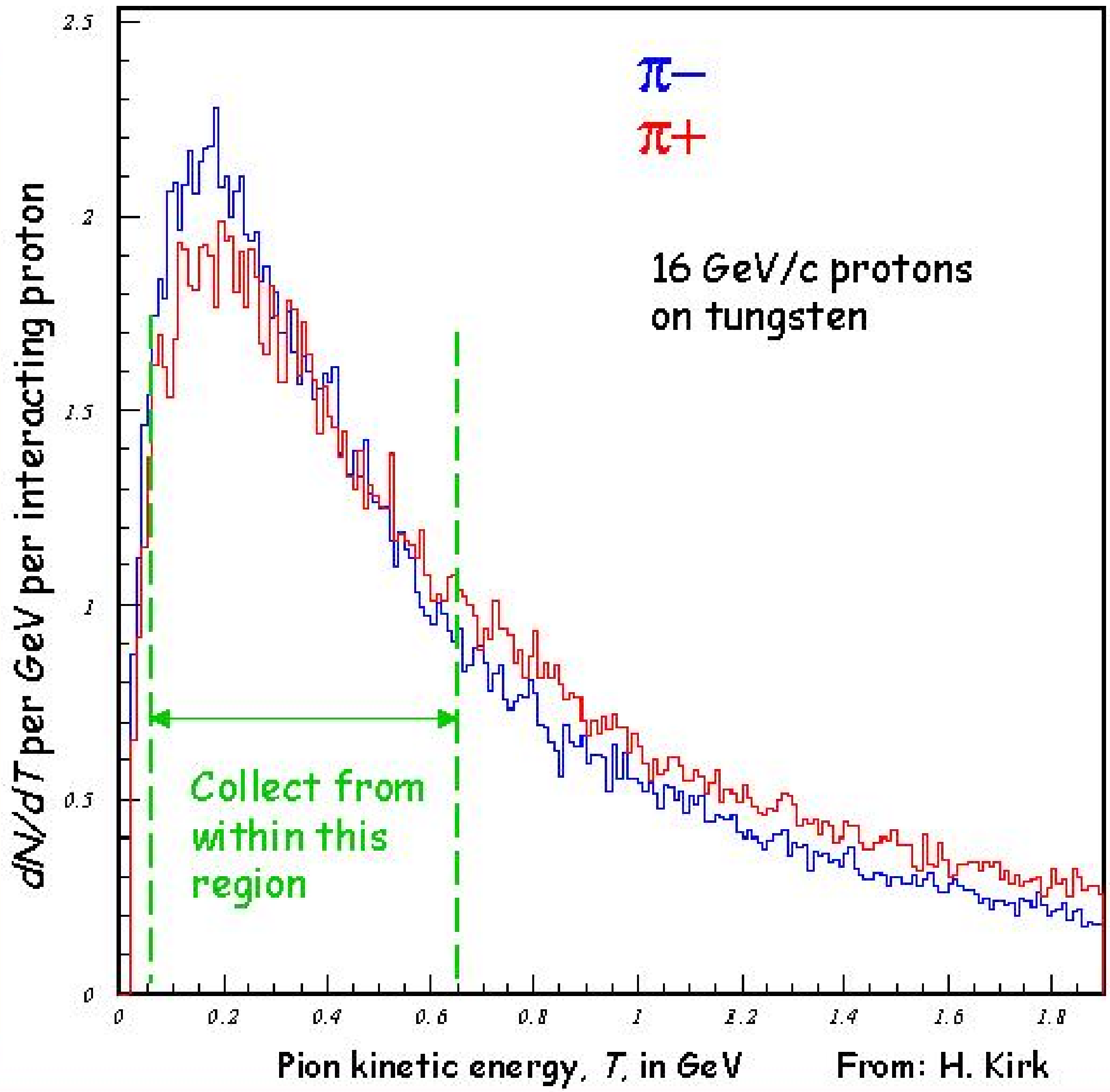
4MW,16 GeV proton beam hits liquid metal target in 20T solenoid
Pions and (then muons) captured in decay channel

Target and Production

We aim to collect and deliver to the first phase rotation channel 0.6 pions of each sign per proton of 16 GeV/c.

In the region of low kinetic energy shown opposite this can be achieved by immersing the production target in a 20 T solenoid field of 75 mm radius. Pions of both signs having transverse momentum of up to 225 MeV/c are focused into the decay channel via the matching channel.

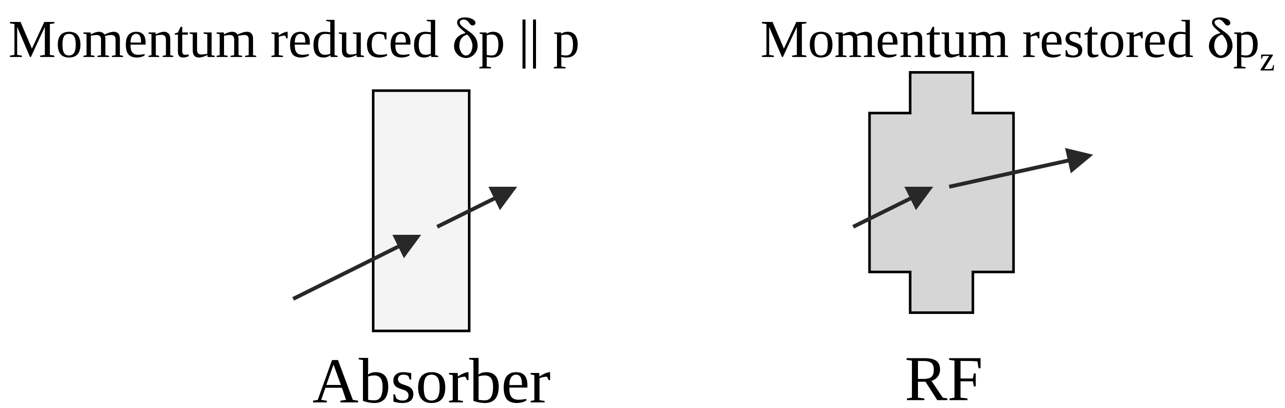
Note that the pion velocity varies from 0.68 to 0.98



From: H. Kirk

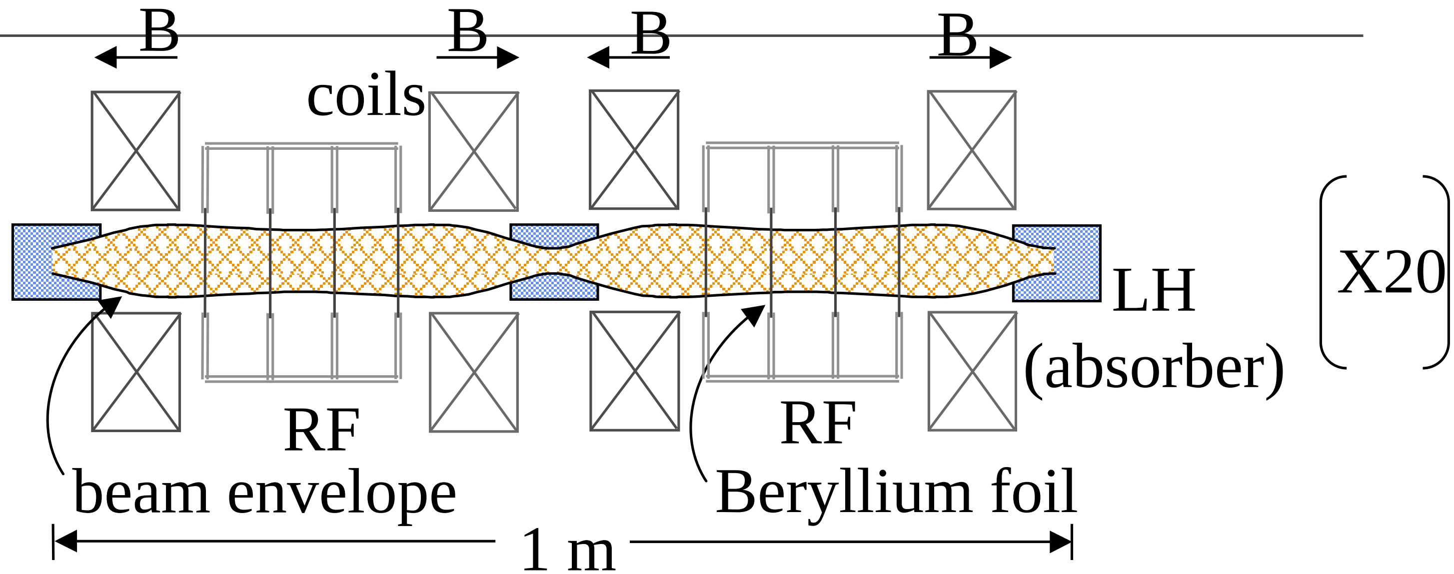
Cooling of 6-D phase space

- Muons from the target are initially captured into a 6-D phase space volume that must be decreased by 10^6 before collision
- Cooling time must be of order τ_μ --distance of order $c\tau_\mu$~660m.
- Ionization cooling (Skrinsky&Parhomchuk,81). Basic Idea



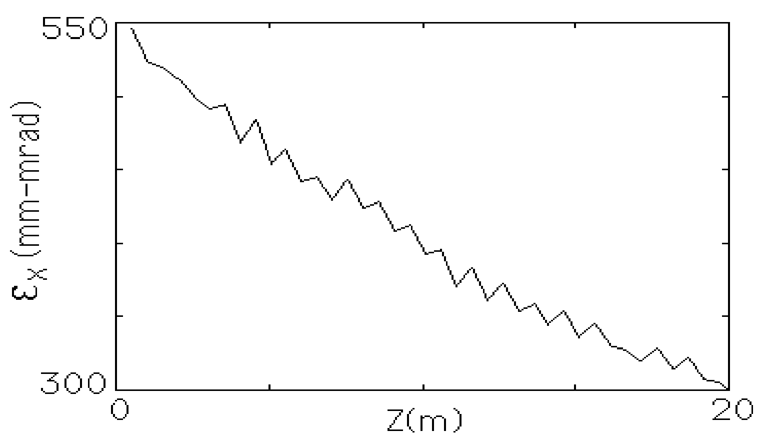
Need to fight multiple scattering and longitudinal blowup

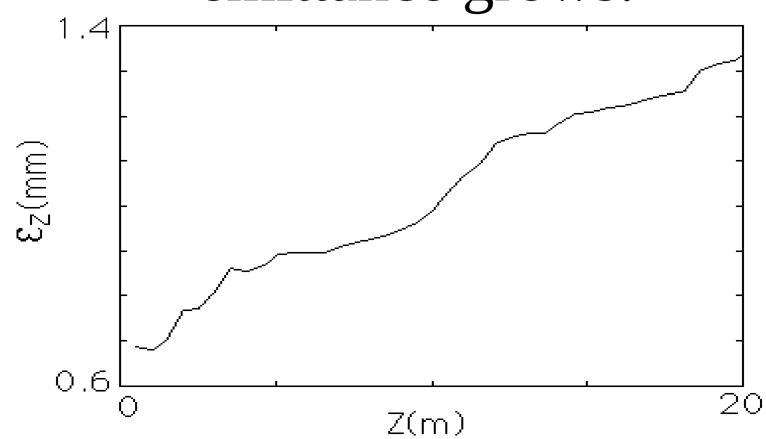
Final Transverse Cooling Section



Transverse emittances are reduced...

while longitudinal emittance grows.

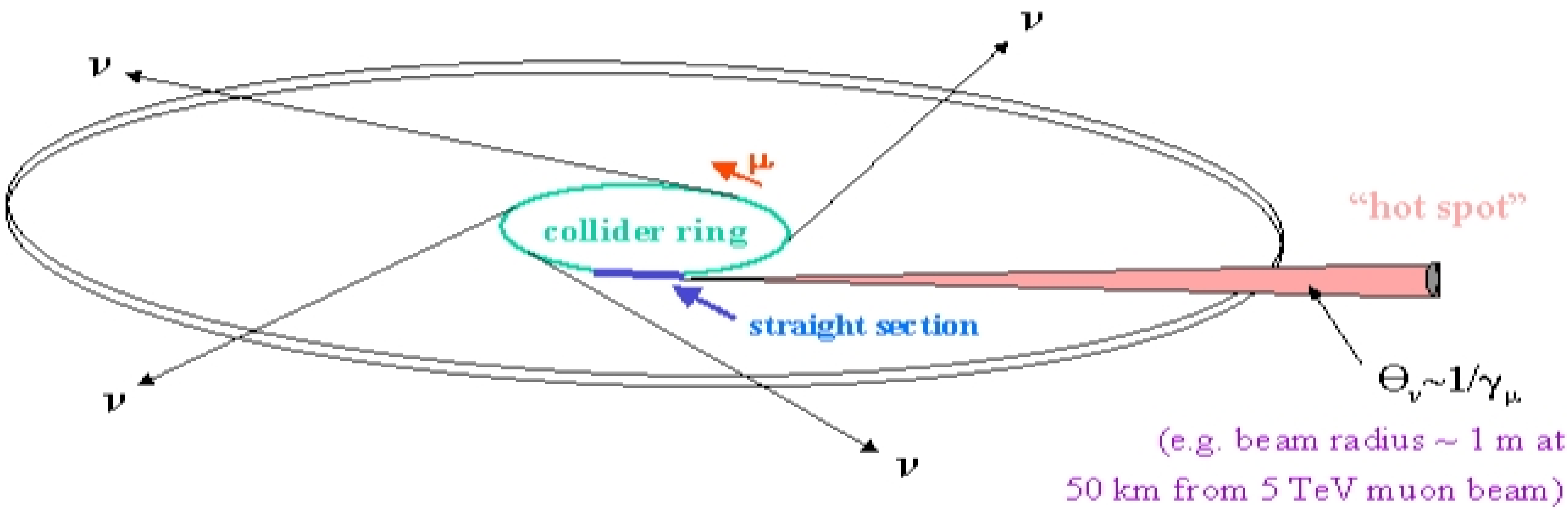




Fernow
Palmer
Kim
Penn

Over 20 m, 6D emittance is reduced by 40%, achieving target value.

Neutrino Production at Muon Colliders



ν beam stronger at str. sections: e.g. even 0.1 m str. section is ~ twice disk average

Radiation ~ Energy^3/depth

3TeV OK at depth of 300m

R&D for Muon Colliders

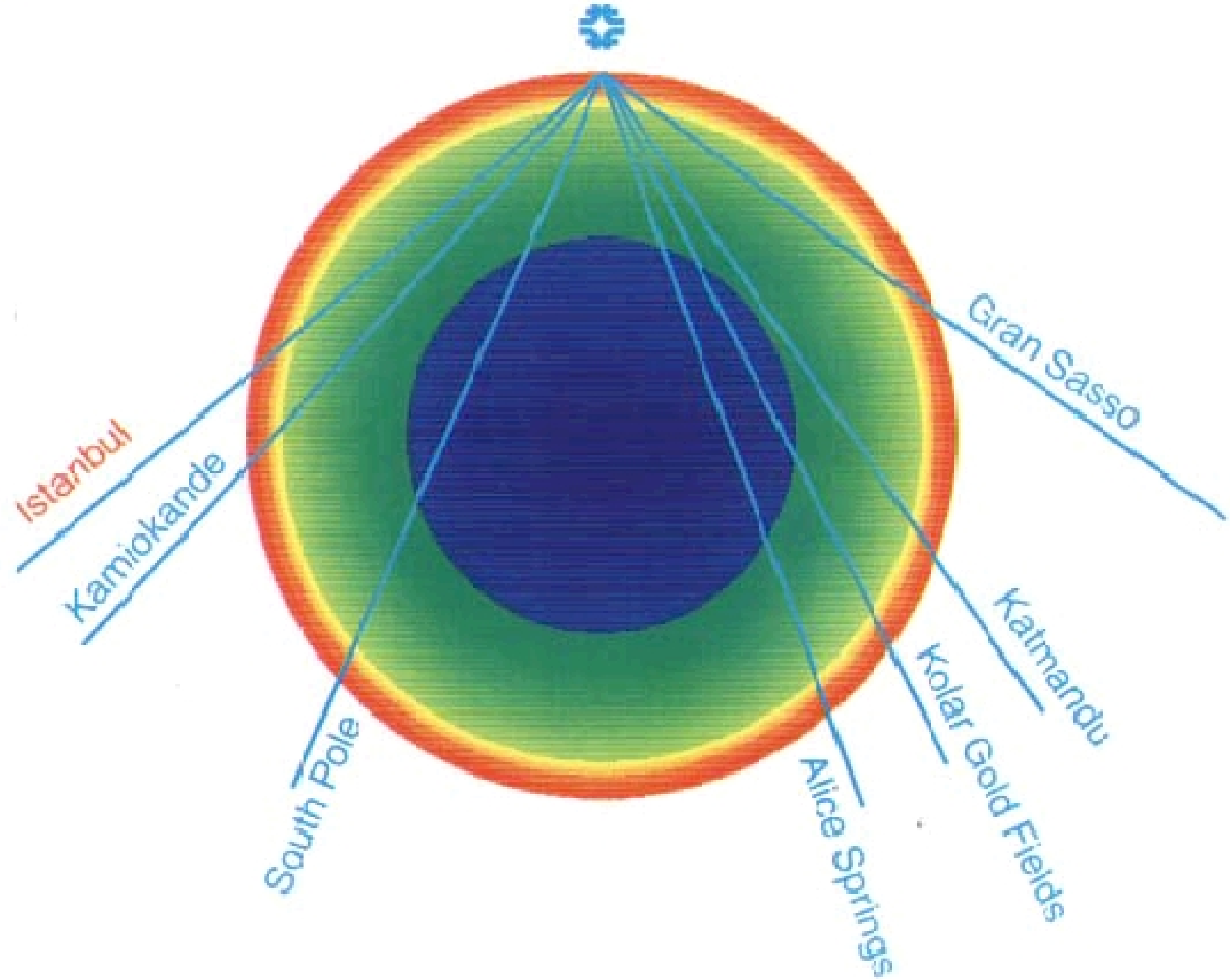
Major Experiments:

- Target: using the AGS (*K. McDonald, et al)* study various target materials, test RF cavity in radiation environment
- Cooling: FNAL (*S. Geer, et al.)*: Test transverse cooling and emittance exchange--Measure input and output phase space of each muon. Goal: develop, prototype, and test all of the critical components needed for a muon cooling channel, and ultimately to build short cooling sections & test them in an appropriate low energy muon beam.

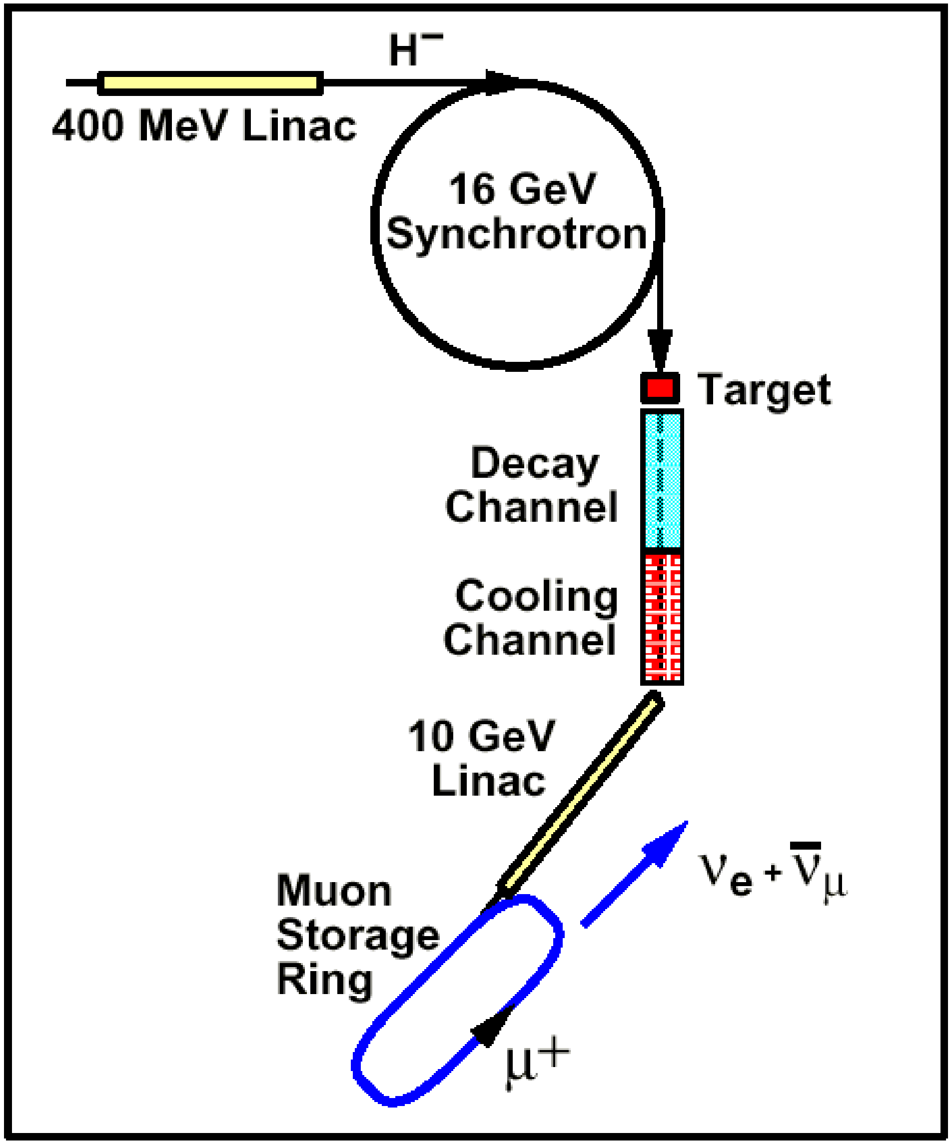
Driver, RF, magnets, lattices, acceleration scheme, collider ring, detector, … have R&D plan/needs, although less critical

- For >3TeV: Improved cooling--- optical stochastic cooling? Compensation of the beam-beam interaction (lithium, plasma). Lowers average power and neutrino radiation. Workshop on 10-100TeV collider (27/9-1/10 1999: pubweb.bnl.gov/people/bking/heshop/)

The Ultimate International Collaboration?



Neutrino Source: Initial Studies



(*S. Geer, C. Johnstone, D. Neuffer, FERMILAB–Pub–99/121*)

- DeRujula, et al., PR99,341(83).
- Geer, PRD 57,6989,1999.
  Alternate looks at machine design: Autin; Palmer, Keil, Johnson;
- Workshop on Physics at the Front End of a Muon Collider, Fermilab, 1997.
- Workshop on the Potential for Neutrino Physics at Future Muon Colliders, BNL, 1998.
- Meeting at LBNL April 1999
- ICFA/ECFA workshop NUFACT'99, Lyon, 1999.Talks
  http://lyoinfo.in2p3.fr/nufact99/
- NUFACT'00 next May (Bay area. Wojcicki/Wurtele, co-chairs).

Neutrino souces and muon colliders

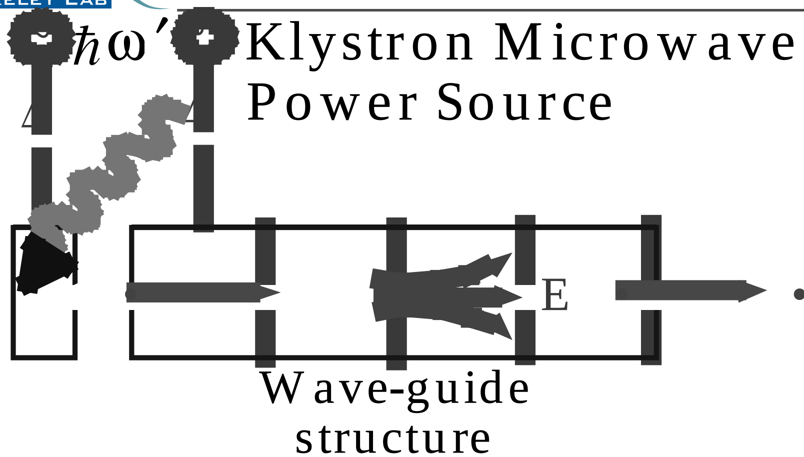
- Requires high power proton source /target and efficient capture, but many other parts are easier, and some are different.

  - No N_μ^2 dependence from luminosity-- bunches less intense, higher-frequency rf.
  - Transverse cooling factor 100 (vs 10^4), no longitudinal cooling.
  - Accelerator chain and storage ring must have large acceptance to minimize cooling requirements (but no small beta sections)
  - The ring may have unusual bow tie or triangle shape--and be tilted.

VLHC Collaboration

- Design affordable machine.
- Baseline 100-200TeV, 100-600kms, L=10^{34}/s-cm^2
- Is synchrotron radiation good or bad?
- Choose magnet and thus tunnel length
- Develop magnet technology
- Overcome hurdle of digging tunnel 100s km in circumference
- Details at www.vlhc.org and http://www-ap.fnal.gov/VLHC/

Plasma-based Linac



Conventional Linac

E_z : 10 - 200 MV/m

L_{int} : km's

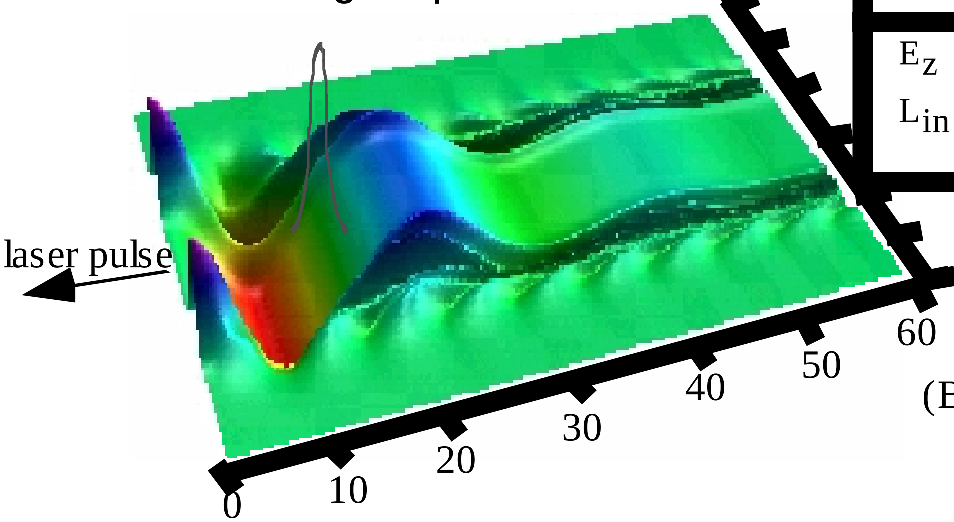
$$W = e\,E_z\,L_{int}$$

Laser driven plasma based linac

E_z : 10 - 100 GV/m

L_{int} : laser diffraction length

Electron beam surfing on plasma electric field



(B. Shadwick, UCB/CBP)

Critical Problems in Plasma Accelerators

- Efficiency
  - Choice of Driver- ebeam or laser
  - Generation of wake

    Coupling, propagation, linear vs nonlinear
  - Acceleration and plasma quality factor

- Beam Quality
  - Particle beam source: Conventional or Optical Injector
  - Accelerating and focusing field structure
  - Instabilities and jitter
  - Halos and background

Important considerations for accelerating structures (plasma and others)

- Method of excitation: ebeam or laser.
- Number of oscillations (Q) of wake
  - limits number of bunches--more charge/bunch at fixed efficiency
- Gradient/stored energy (loss factors k_n)
  - Determines beam dynamics and stored energy requirements
- Dark Current *(Nonlinear kinetic plasma physics)*
  - Must be controlled for high-energy applications
  - High gradient (~100GeV/m) plasma experiments operate in this regime. Earlier results (e.g., Joshi et al) achieved ~1.5GeV without dark current.
  - Limitations unclear

Recent Experimental Advances

- High Gradients demonstrated with unstable laser pulse breaking up in plasma (no injection of electrons), >100GeV/m.

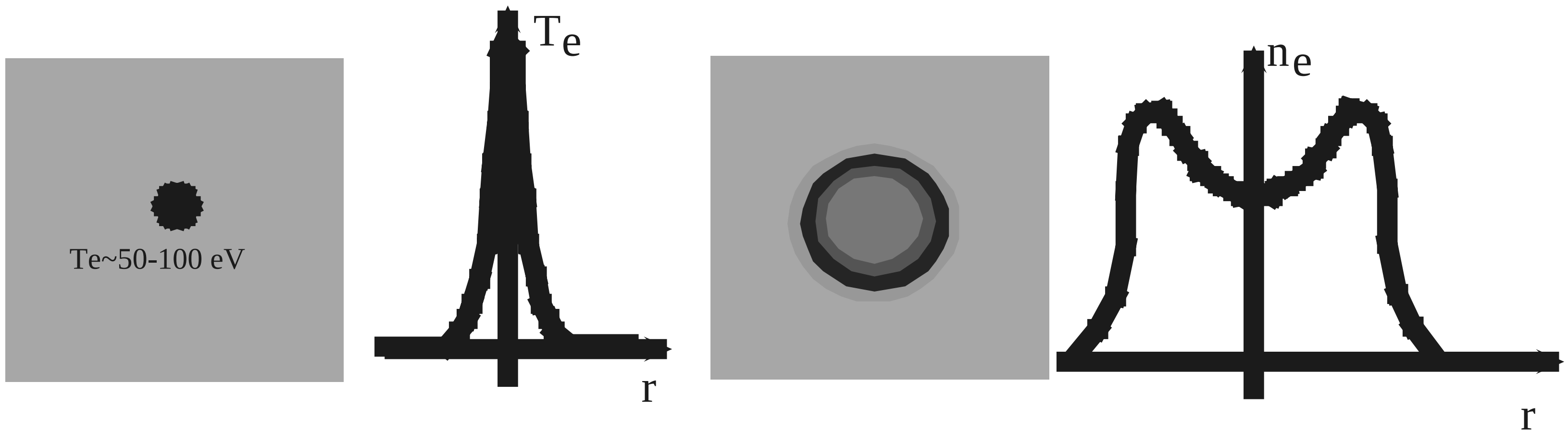
(e.g.,Umstadter, et al, Science 273,472 (1996);Gordon et al, PRL 80, 2133 (1998))

  - Disadvantages for accelerators: Based on instability (phase problems), requires low ω_p/ω---rapid dephasing of particles and wake
  - Preferable to have "Laser Wakefield Acclerator" --pulse length ~ c/ ω_p

- First acceleration of injected electrons in Laser Wakefield Acclerator: 1.5 GeV/m, 1.5MeV acceleration. (Dorchies et al, Phys. Plas. 6, 2903 (1999)).
- Guiding of high laser powers (>10^{17}W/cm^2) in channel for ~10 diffraction lengths, low intensity for 100 diffraction lengths
- Acceleration in channel is critical
- Recent review: Esarey, et al, IEEE Trans. Pl. Sci. 24,252 (96); Proc. of the AAAC98 workshop.

Channel Creation*

Ionizing and Inverse Brehmsstrahlung Heating a thin cylinder of gas leads to hydrodynamic expansion and a Plasma Channel with a density minimum on axis is formed.



Heated Plasma Spark creates a Hydrodynamic shock that leaves a density minimum on-axis

*C. J. Durfee et al. Phys. Rev. E, v. 51, no. 3, 2368 (1995)
P. Volfbeyn et al. Phys. Plasmas, v. 6, no. 5, 2269 (1999)

Ehrlich, et al, PRL 77, Dorchies et al, PRL 23, 4655 (1999);-capillary

Ultra-Relativistic Beam-Plasma Dynamics

- *Goal:* Develop diagnostics, benchmark simulations, improve design tools, understand plasma as a *dynamic* element of a accelerator.
- Experiments: UCLA,USC,LBNL, BINP,SLAC E150 & E157

Is a multi-GeV beam driver superior to a laser?

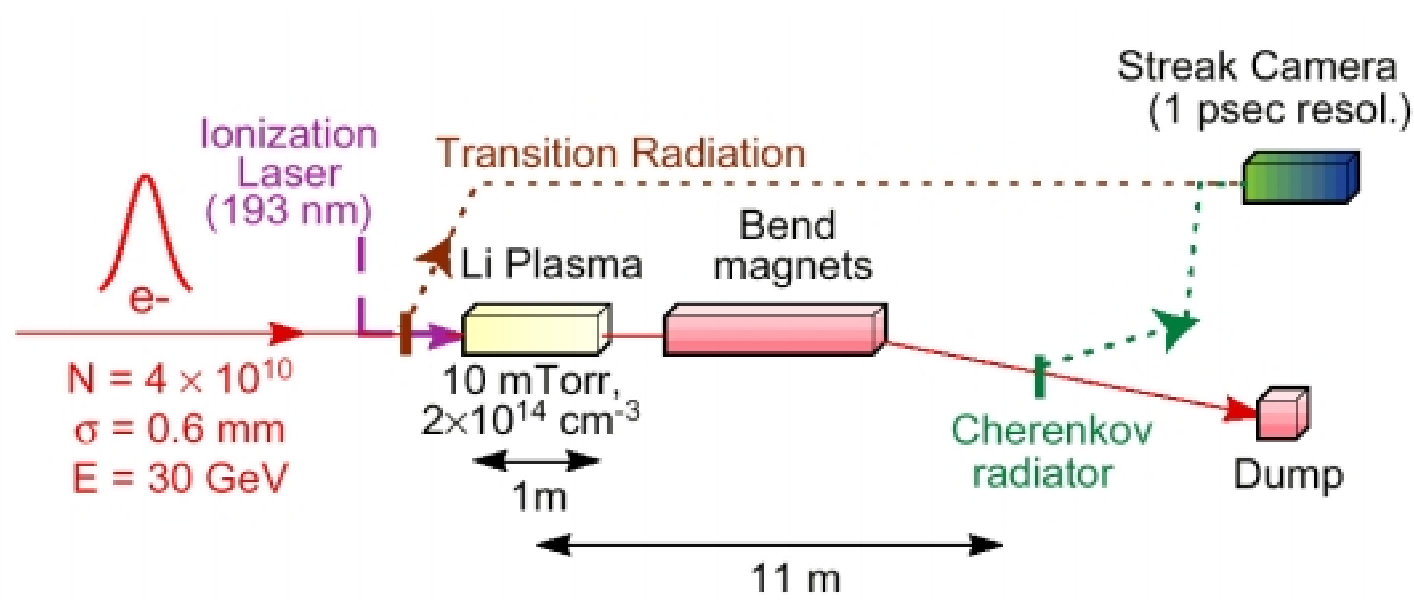
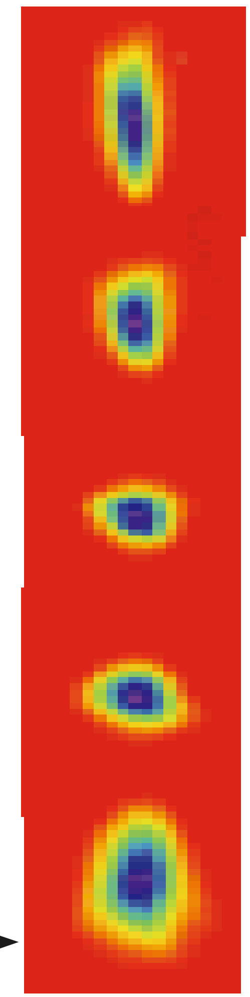


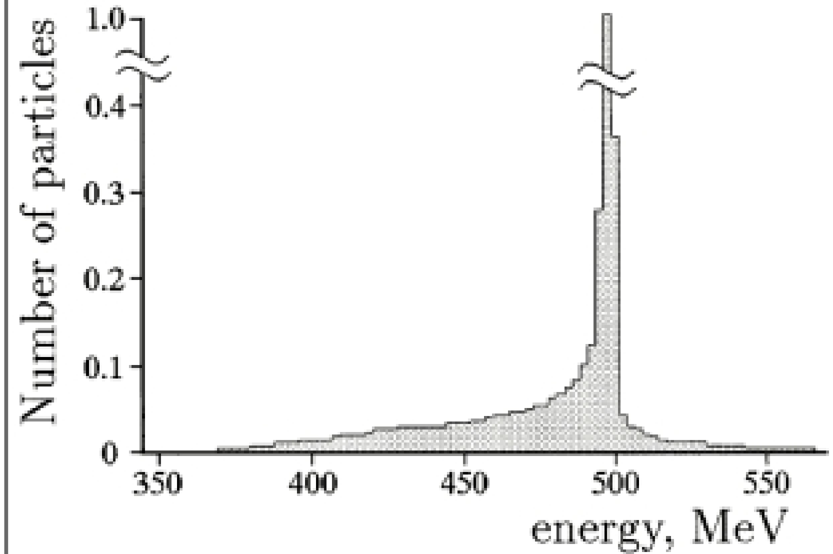
Figure 1: Layout of E-157 (PAC99).



Transition radiation diagnostic of beam size with quad scan

The BINP beam-driven plasma linac

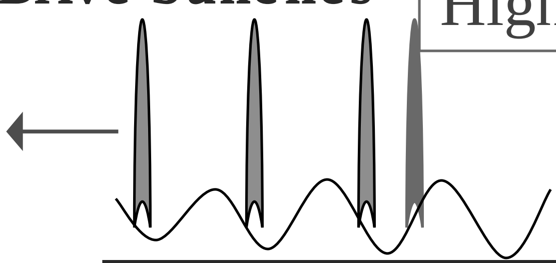
- Density: 10^{15} /cm^3
- Gradient: 1GeV/m, 100 stages @ 10m each
- Final energy: 1TeV,energy spread 3%, N=5X10^9,
- Excitation by train of drive pulses
- From Kudryatsev et al. in Proc. ICFA workshop on Advanced Accelerators, NIM 410, 1998. Also work by Chen, Katsouleas, Nakajima,Rosenzwieg, others.



Predicted performance of initial experiment at BINP

Drive bunches

High energy bunch



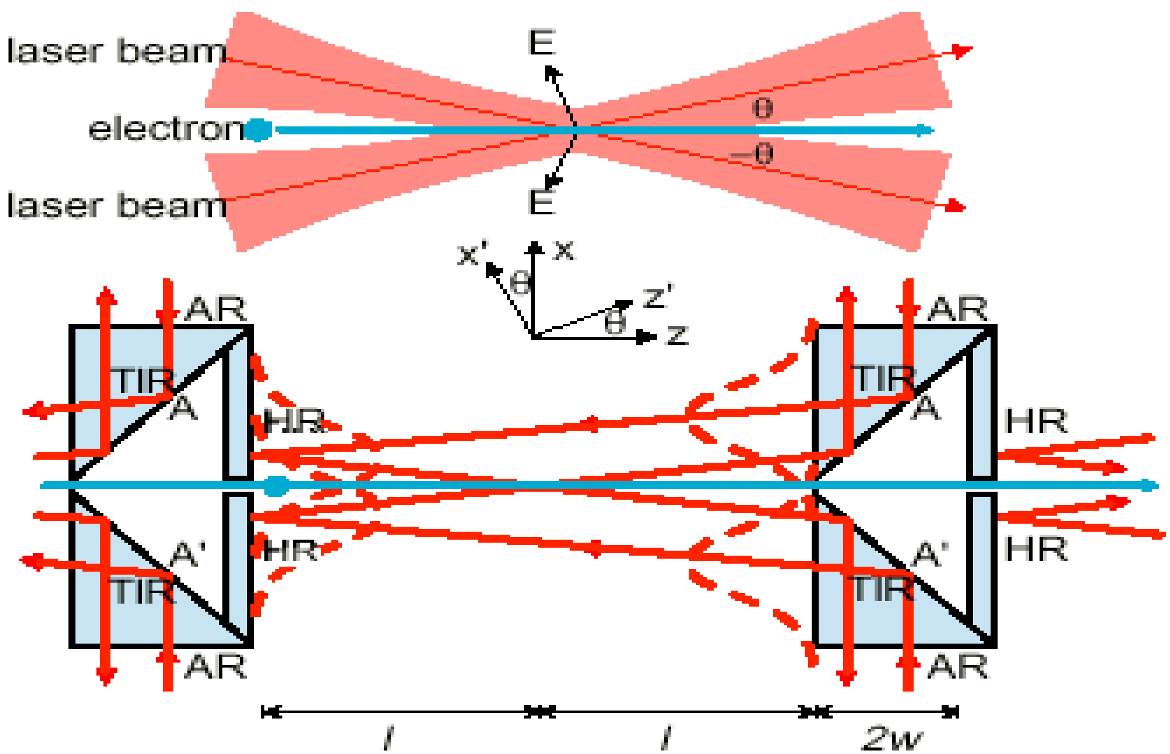
Summary: Plasma-based concepts

- Significant progress in plasma-based concepts: Experiment, theory, simulations, diagnostics.
- Next few years:
  - LASER driver: High power (10^{18}W/cm^2) propagation (L>> Z_r) and wake generation in channels
  - BEAM driver: Ultra-relativistic dynamics in plasmas (SLAC E150/E157)
  - Short bunch generation: Optical injection
  - Dark current limits
  - *Plasma structure design*--Femtosecond engineering
- For the future: High energy, beam quality and intensity, staging, efficiency

Vacuum Acceleration

- Laser (no plasma): Construct and excite small scale overmoded structures. Directly use the intense electric field of the laser.
- Issues: very short bunch length, structure damage, wakefields.
- A schematic (Laser Acceleration Experiment, Byer et al.). Bunch from

Stanford FEL. Accelerate 330keV at ~1GeV/m:

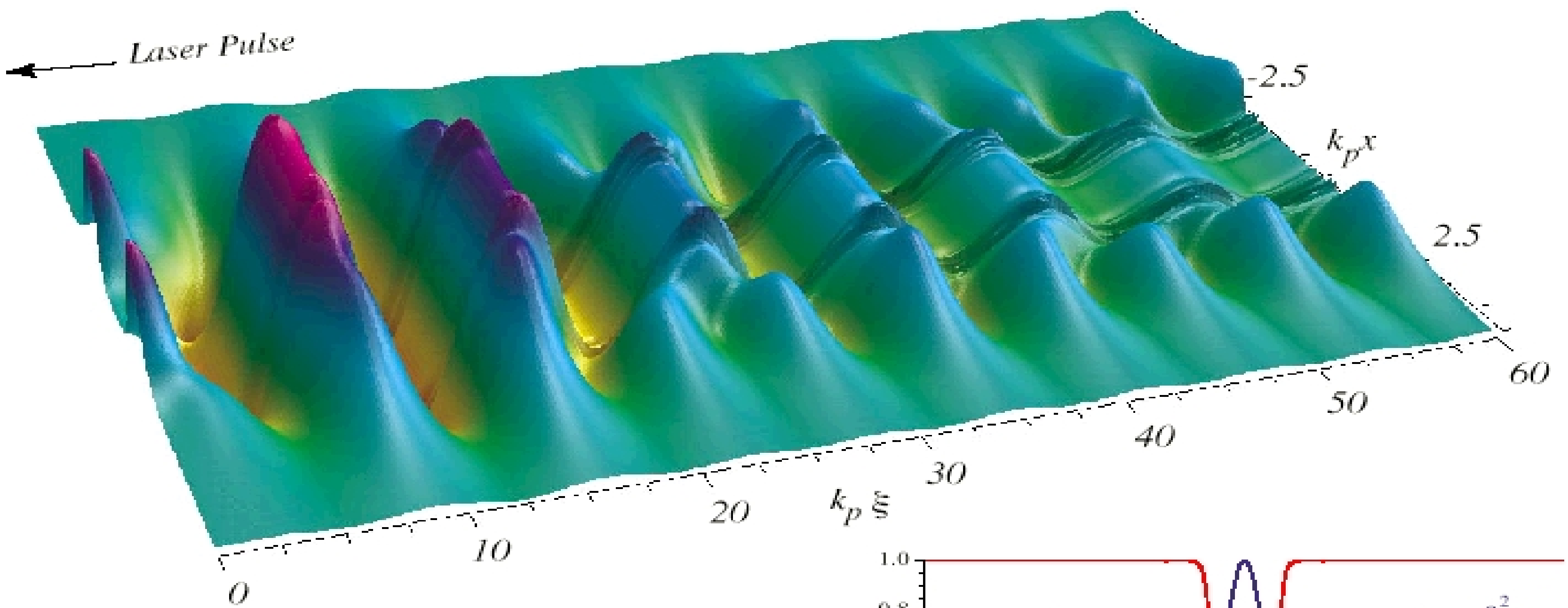


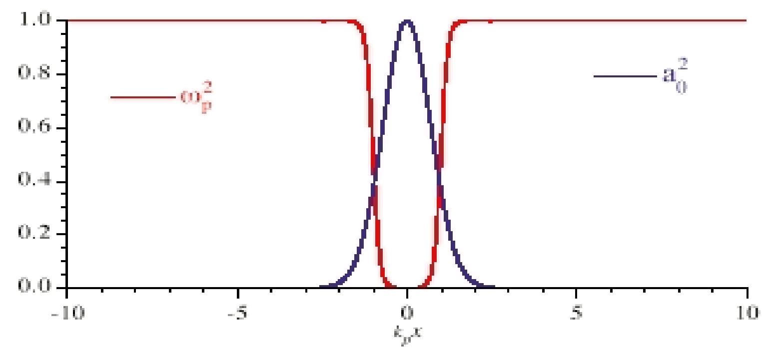
Summary

- Many ideas for solving critical problems towards building high-energy colliders. There are no obvious “show stoppers” for any of the schemes--but *strong* opinions on the correct direction to proceed. Even if all fail, a clever student may come up with a better idea!
- Significant research ongoing involving extended collaborations of laboratories and universities
- The timescale for investigating these concepts is longer than most would like.
- This research may yield machines of interest, *perhaps* neutrino sources, that can, hopefully, be built with less cost and complexity a collider.
- The next generation colliders will not be the last!

Longitudinal Wake Field

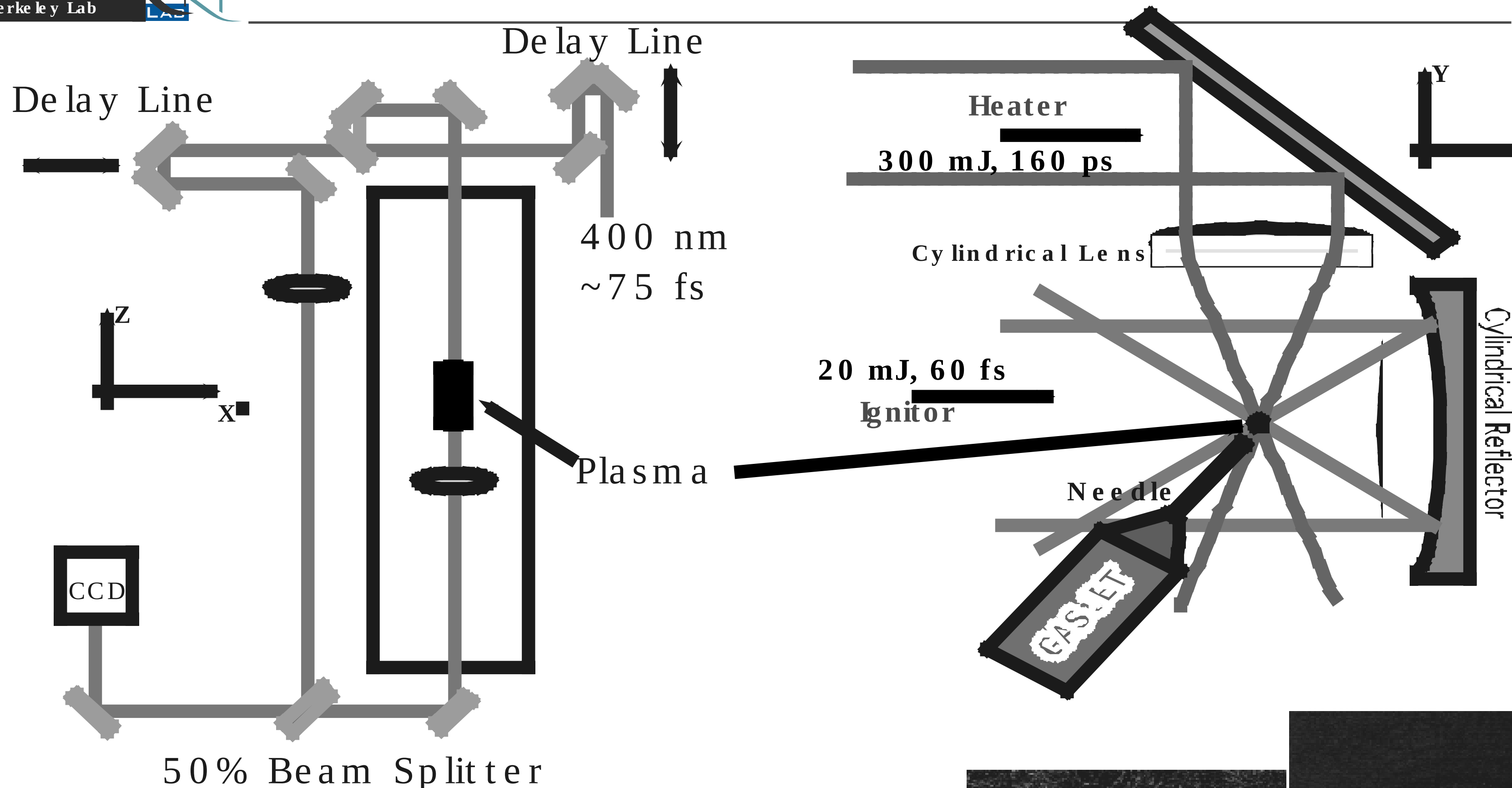
Numerical Solution of the Linearized Cold Fluid Equations



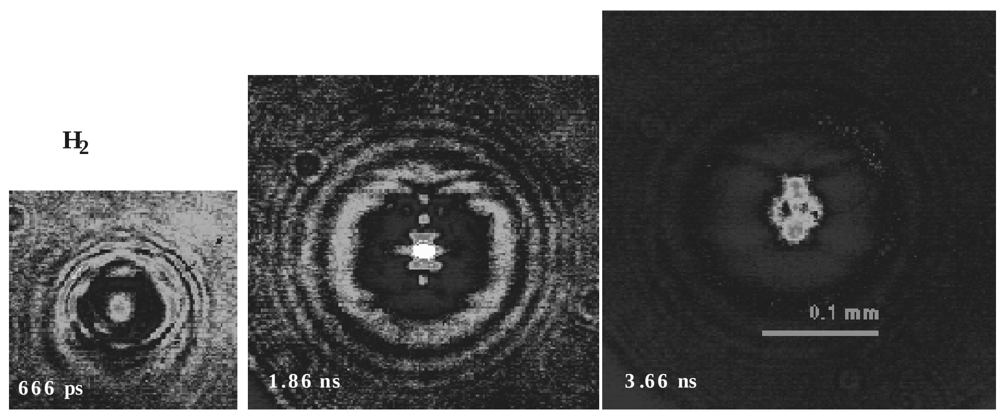


B. A. Shadwick, J.S. Wurtele, UC-Berkeley 1997

Ignitor-Heater Plasma Channel Creation Method*



Transverse Interferometry With Femtosecond Resolution



*P. Volfbeyn et al. Phys. Plasmas, v. 6, no. 5, 2269 (1999)

Beam-plasma interaction

- Need to understand plasma as optical element, but
  - Response is dynamic (z-ct)-dependent over distances in bunch of order c/ω_p
  - Electrons and positrons have different focusing properties
  - When plasma response is linear, beam is non-linearly self-pinched in its own B-field
  - When plasma gives linear focusing of beam, the plasma response is highly nonlinear.
  - Example of theory/simulation: overdense plasma, no return currents. Equivalent to self-gravitating system. In slab geometry there is understanding of emittance growth as a function of initial beam properties in the self-pinch--overdense-- plasma lense. Theory and simulation of emittance growth K. Backhaus:

Beam Transport in Slab Plasma