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international centre for theoretical physics

ICTP 40th Anniversary

H4.SMR/1574-1

"VII School on Non-Accelerator Astroparticle Physics"

26 July - 6 August 2004

Future Accelerators, Muon Colliders, and Neutrino Factories

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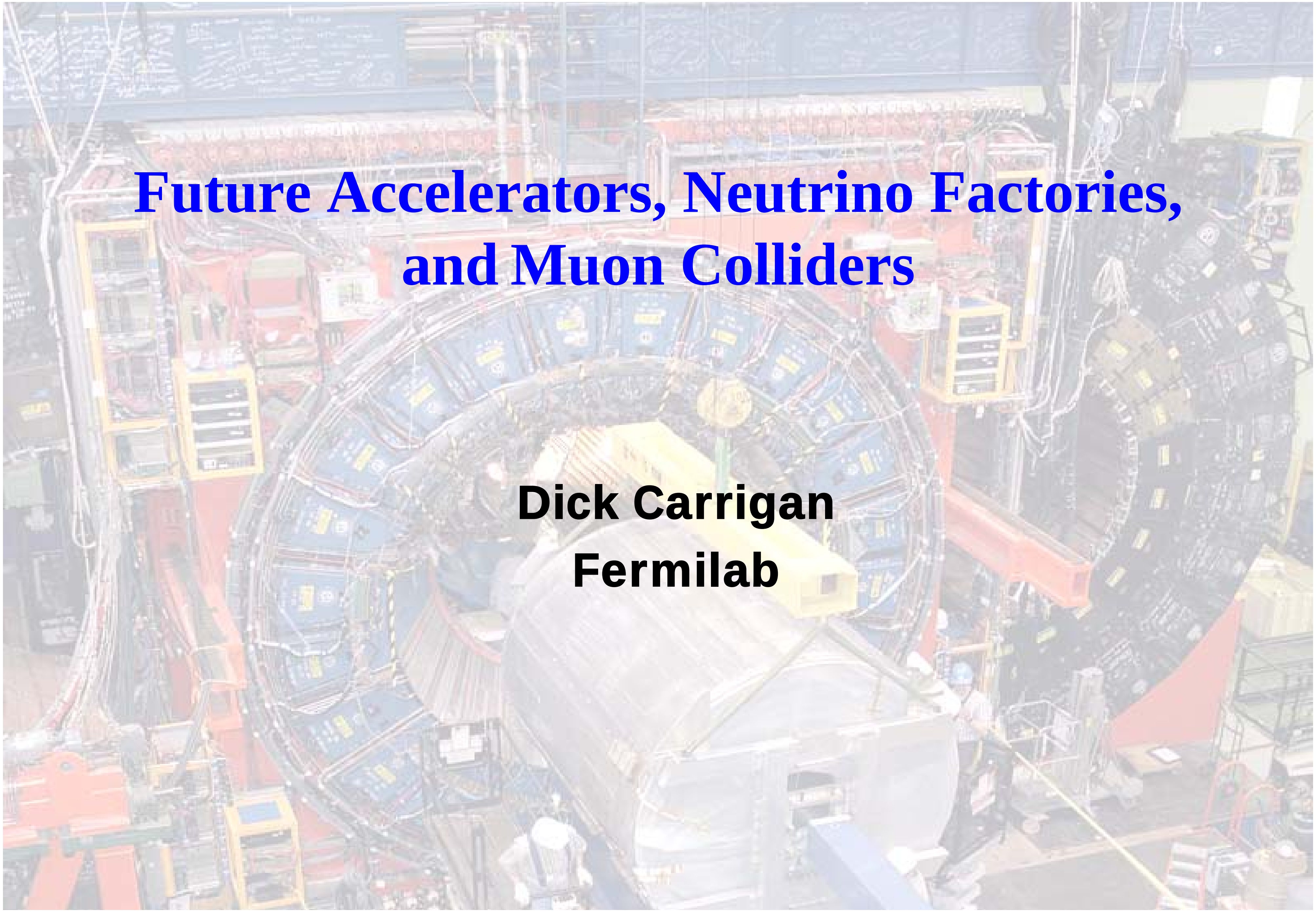


Future Accelerators, Neutrino Factories, and Muon Colliders

Dick Carrigan

Fermilab

Six great questions

- SM, SUSY, Higgs
- extra dimensions-may be related to SUSY
- neutrino mass and oscillations
- Missing mass and energy
- origins of CP
- none of the above

Plan of Talks

- Current status
  - Tevatron, LHC
  - accelerator technologies
- Midrange possibilities
  - Linear colliders
    - gamma-gamma colliders
    - free electron lasers
  - Neutrino Facilities
    - NUMI
    - proton drivers
    - neutrino factories
    - muon colliders
  - Very large hadron colliders
- Visionary possibilities
  - laser accelerators
  - plasma accelerators

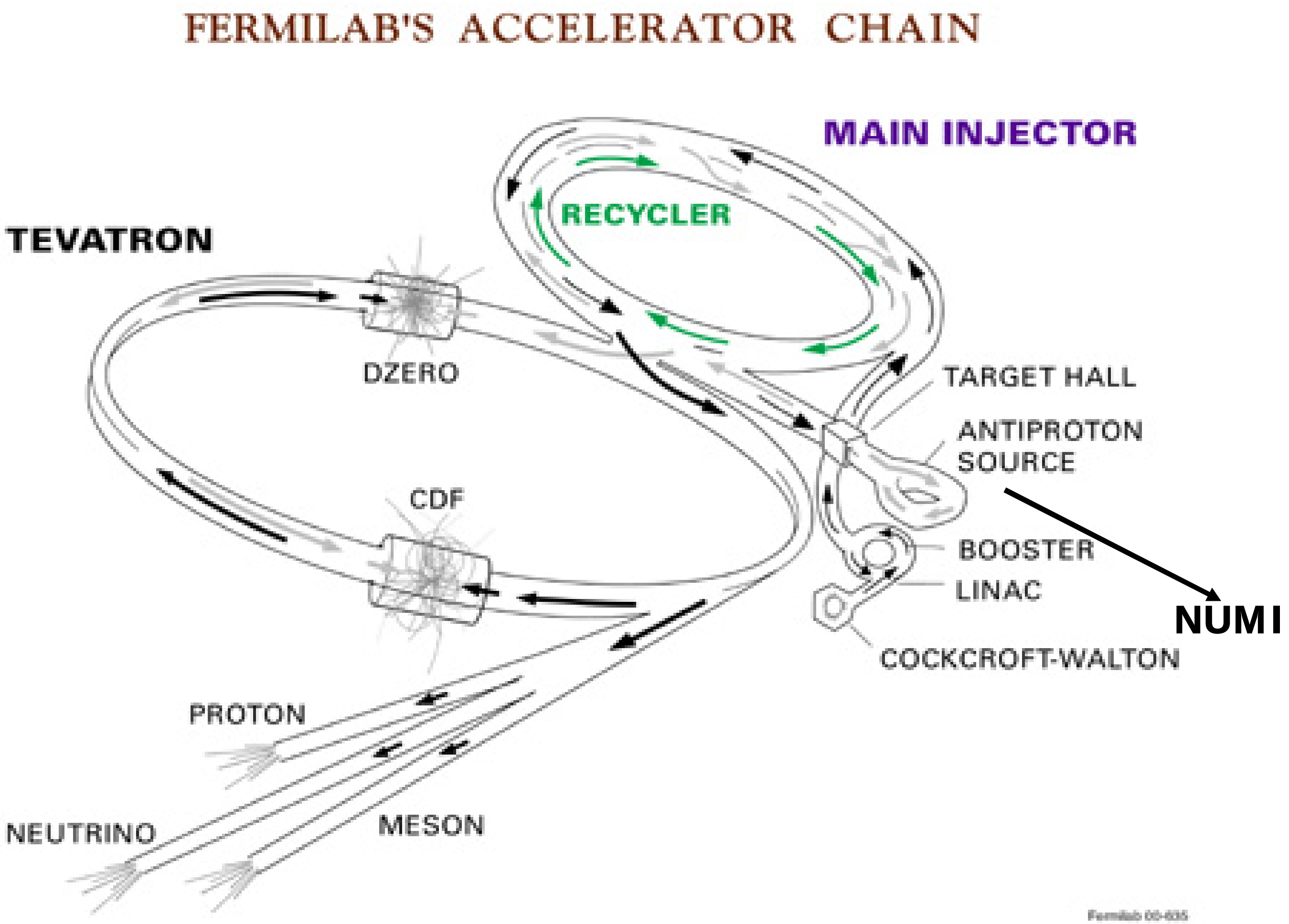
Accelerators and storage rings in operation or underway

The Tevatron

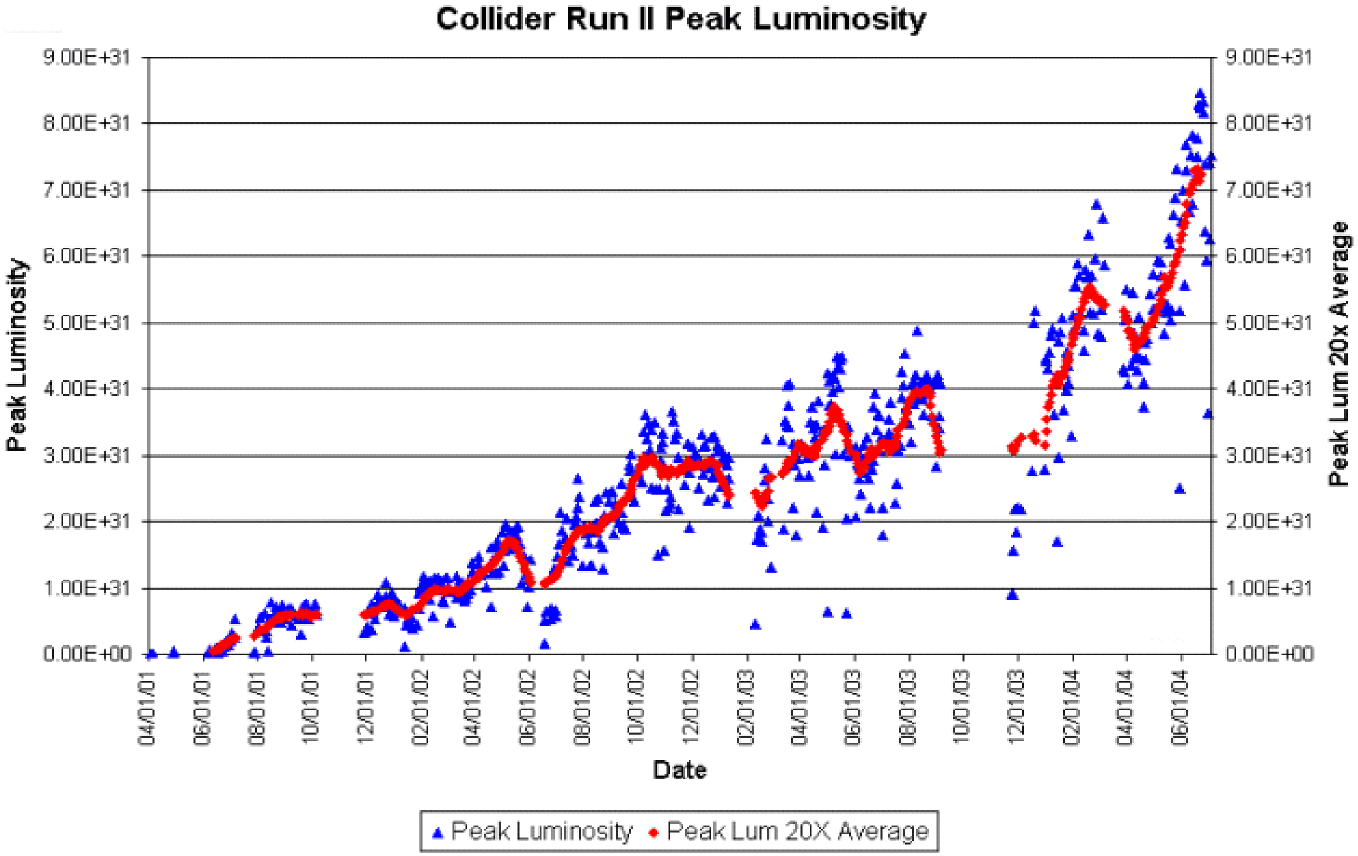
LHC-this is the 800 lb gorilla of the future
(about 2007)

The Tevatron

Tevatron schematic

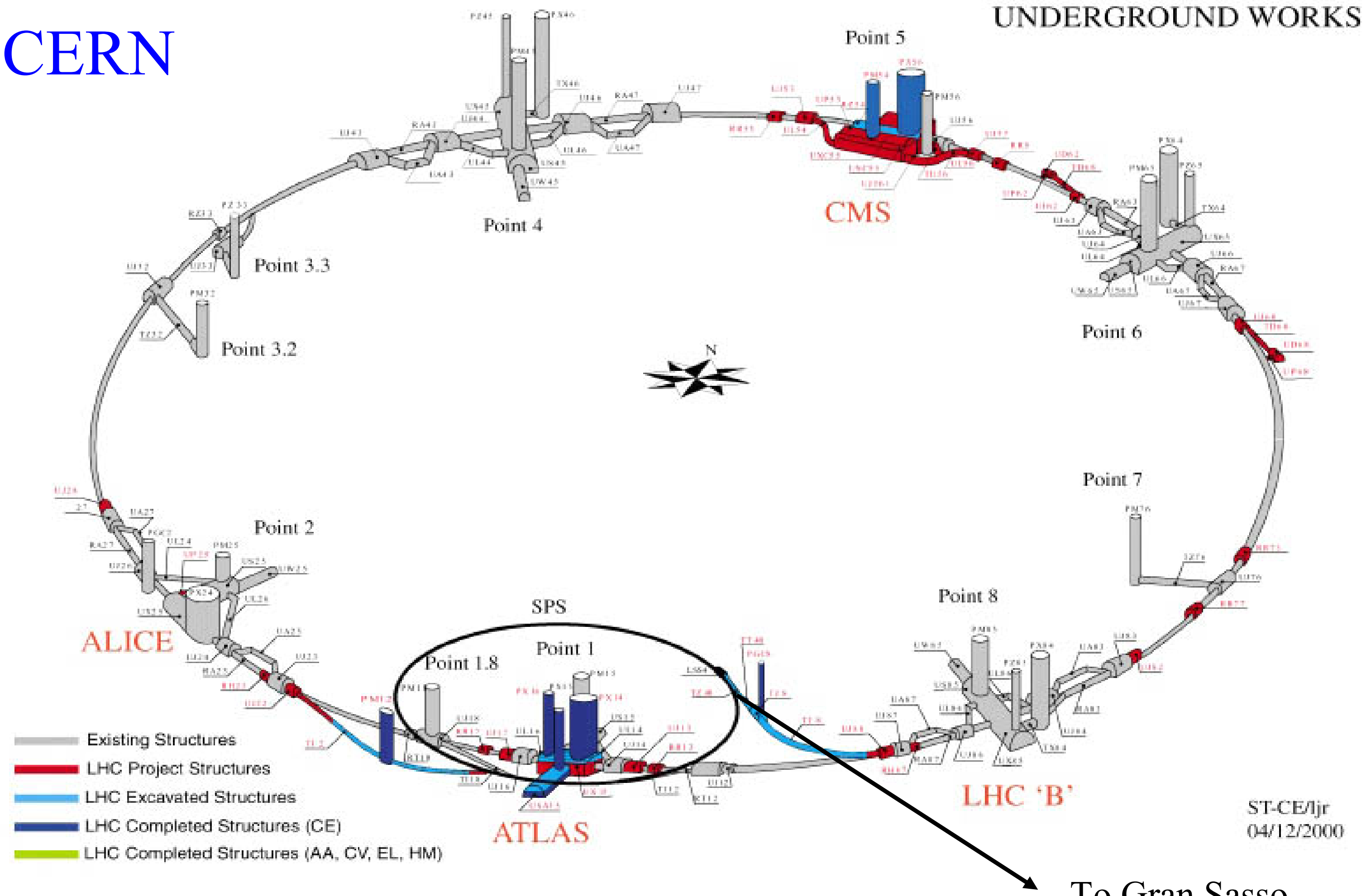


Tevatron luminosity



Peak as of July 7, 2004 is 92.1E30 $cm^{-2}s^{-1}$

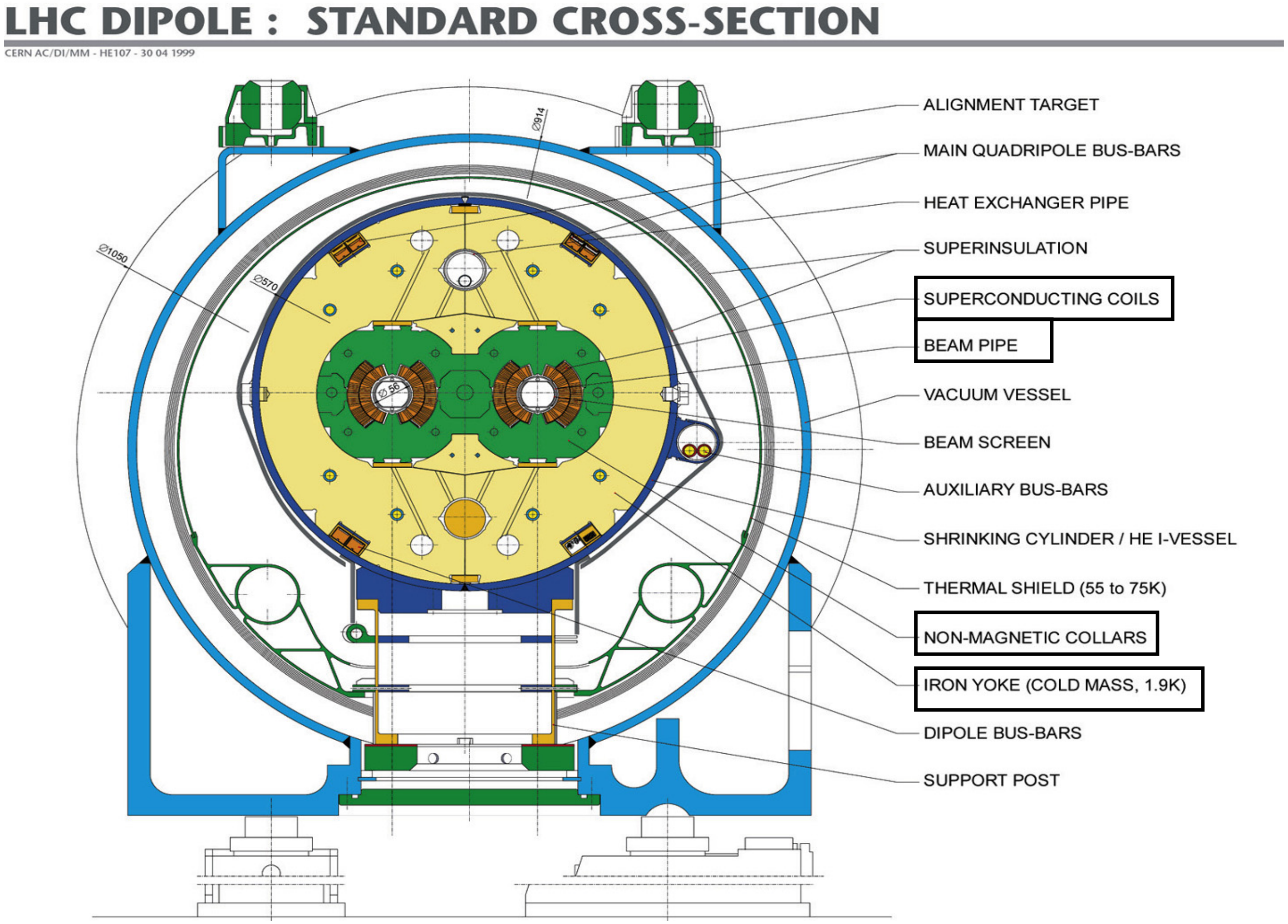
LHC at CERN



To Gran Sasso

14 TeV L= $10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$

LHC magnet


LHC DIPOLE : STANDARD CROSS-SECTION
CERN AC/DI/MM - HE107 - 30 04 1999
Ø914
Ø1050
Ø570
Ø56
ALIGNMENT TARGET
MAIN QUADRIPOLE BUS-BARS
HEAT EXCHANGER PIPE
SUPERINSULATION
SUPERCONDUCTING COILS
BEAM PIPE
VACUUM VESSEL
BEAM SCREEN
AUXILIARY BUS-BARS
SHRINKING CYLINDER / HE I-VESSEL
THERMAL SHIELD (55 to 75K)
NON-MAGNETIC COLLARS
IRON YOKE (COLD MASS, 1.9K)
DIPOLE BUS-BARS
SUPPORT POST

Physics and technology of accelerators

References

Edwards and Syphers, Tigner and Chao

ion sources (anti proton accumulation a special case)

acceleration-via RF (a limit for linear colliders)

bending -via magnets-typically superconducting at high energy (a limit)

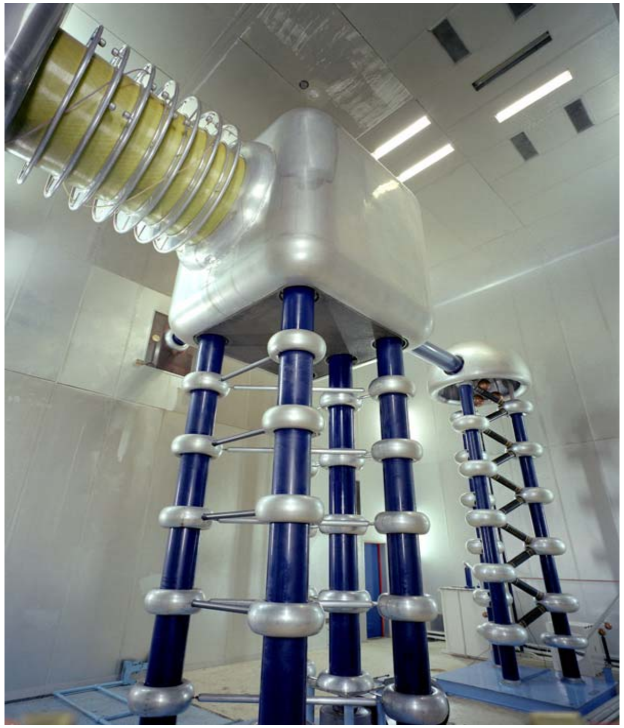
focusing

colliders-luminosity important

an enclosure (limit)

Ion sources

Fermilab
Cockcroft-Walton



Fermilab
Anti-proton source

Acceleration

Fermilab Linac
RF cavity

An enclosure

Tevatron tunnel with old Main Ring in place

Mid-range possibilities

- Linear colliders
  - gamma-gamma colliders
  - free electron lasers
- Neutrino facilities
  - NUMI
  - Proton drivers
  - neutrino factories
  - muon factories
- Very large hadron colliders

Mid range possibilities: linear colliders

done at SLAC with 50 GeV on 50 GeV

<u>need</u>

- 500 –1000 GeV total energy
- L= 10^{34} /cm^{2}s… luminosity

<u>physics reach</u>-must compliment LHC

- Glashow-Lane skeptical (DOE 4/2001)
- polarization important
- Butler-sit, span (pk ener), scan-possible
  - 300 fb^{-1} and 250 fb X sec
    - gives 75 K Higgs O(1 yr)

linear colliders - continued

possibilities

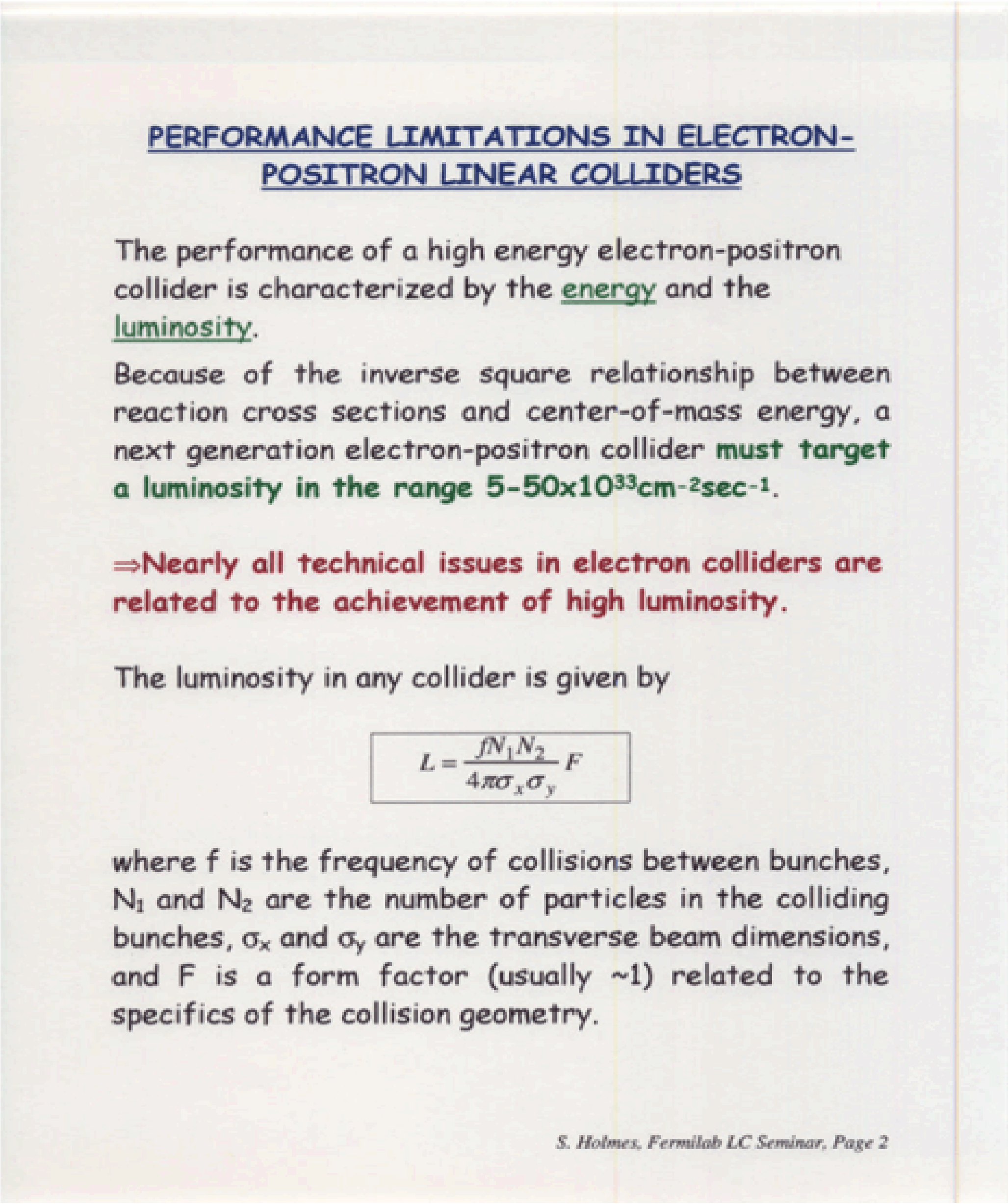
JLC (Japan), NLC (US), TESLA (DESY),
CLIC (CERN)

political process – technology choice end of 2004

build a test bed somewhere?

gamma-gamma collider

Linear Collider luminosity



PERFORMANCE LIMITATIONS IN ELECTRON-POSITRON LINEAR COLLIDERS

The performance of a high energy electron-positron collider is characterized by the energy and the luminosity.

Because of the inverse square relationship between reaction cross sections and center-of-mass energy, a next generation electron-positron collider **must target a luminosity in the range 5-50x10^{33}cm^{-2}sec^{-1}**.

⇒Nearly all technical issues in electron colliders are related to the achievement of high luminosity.

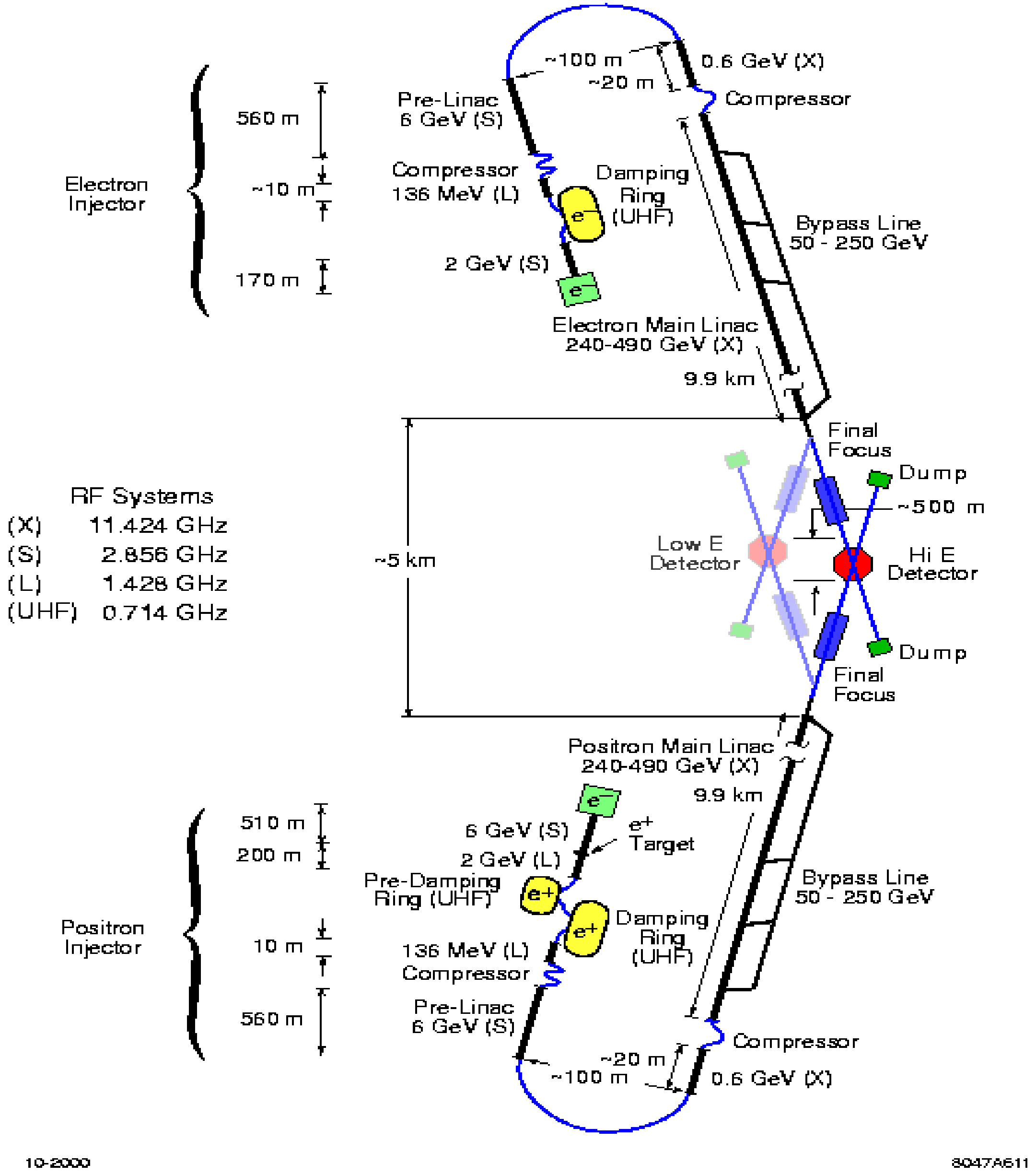
The luminosity in any collider is given by

$$\boxed{L = \frac{f N_1 N_2}{4\pi\sigma_x\sigma_y} F}$$

where f is the frequency of collisions between bunches, N_1 and N_2 are the number of particles in the colliding bunches, σ_x and σ_y are the transverse beam dimensions, and F is a form factor (usually ~1) related to the specifics of the collision geometry.

S. Holmes, Fermilab LC Seminar, Page 2

NLC-Warm RF

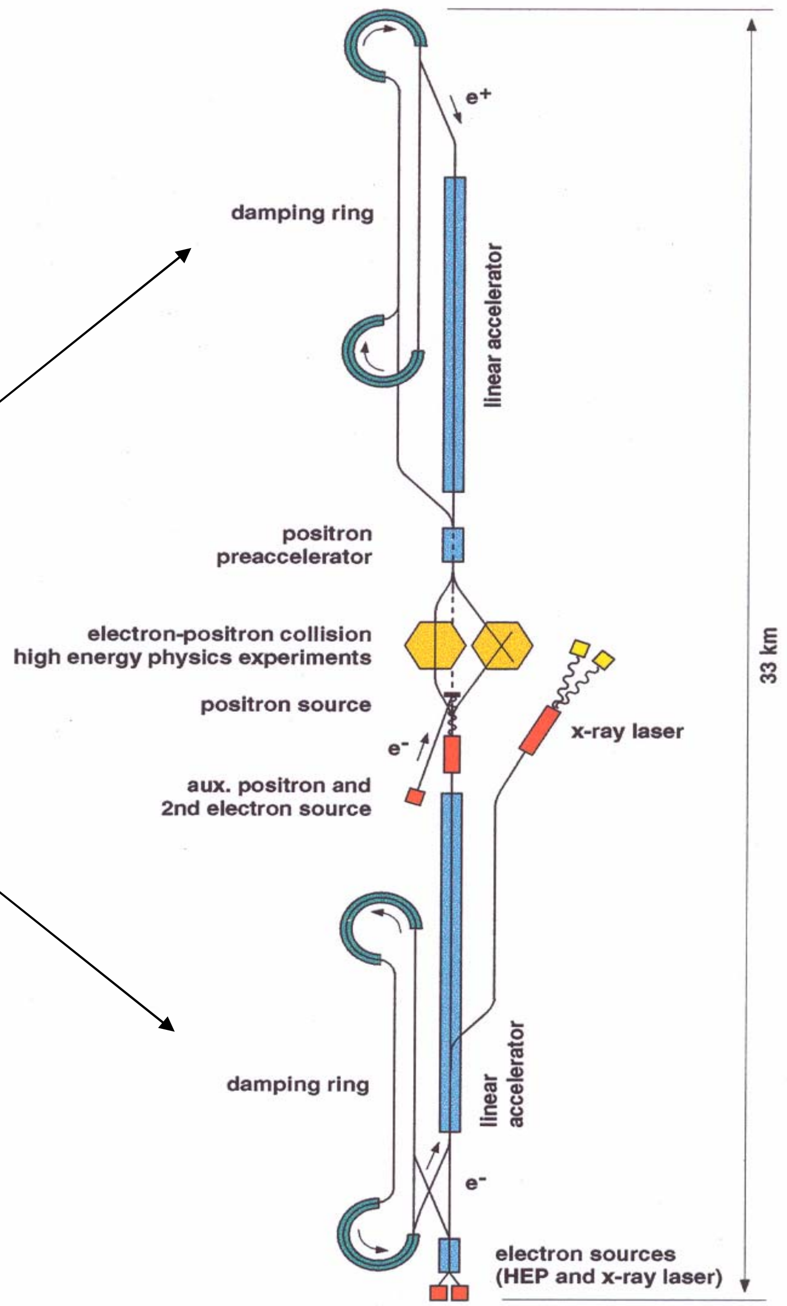


RF Systems

(X)	11.424 GHz
(S)	2.856 GHz
(L)	1.428 GHz
(UHF)	0.714 GHz

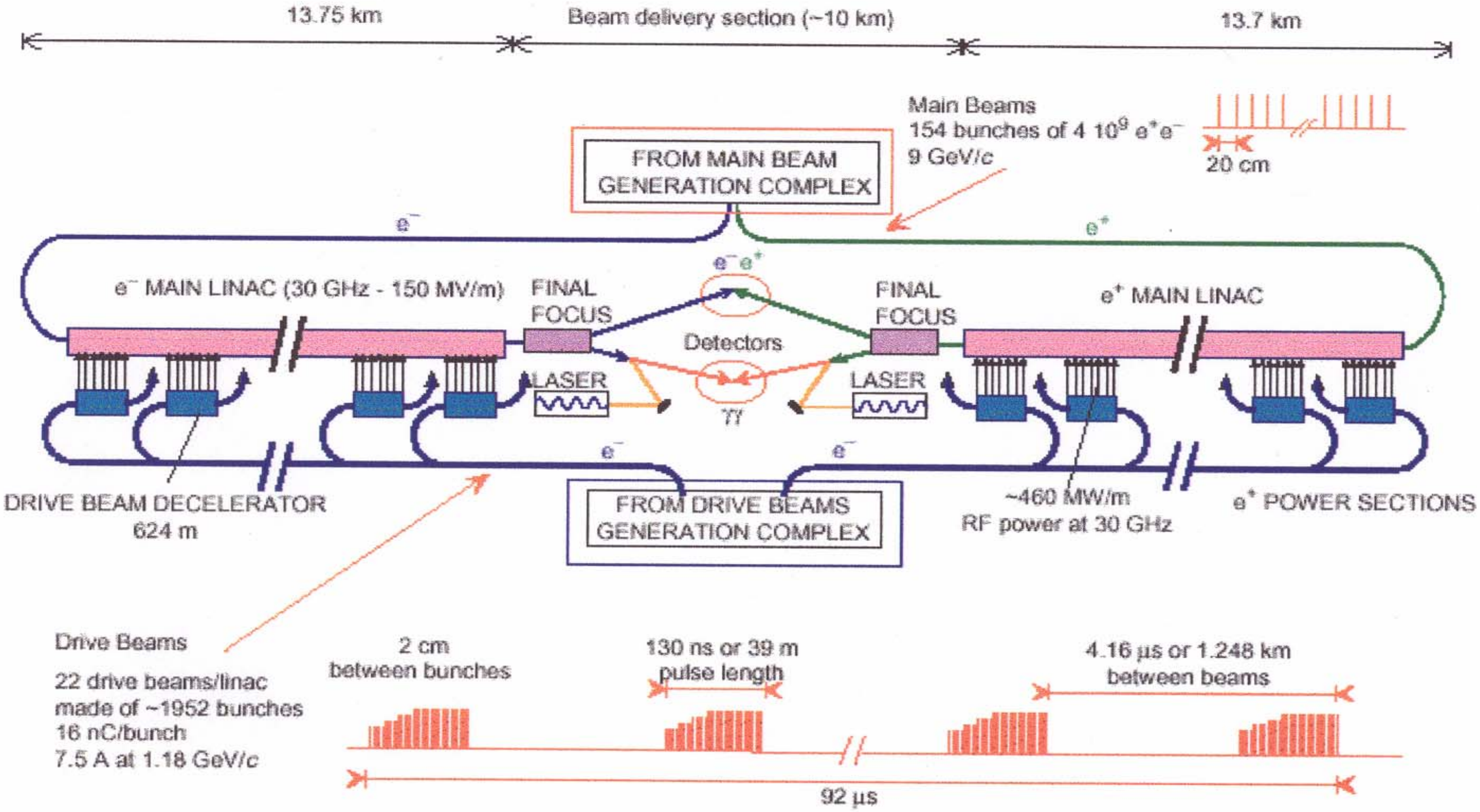
Tesla-
Cold RF

Note big damping rings



DESY-Tesla layout

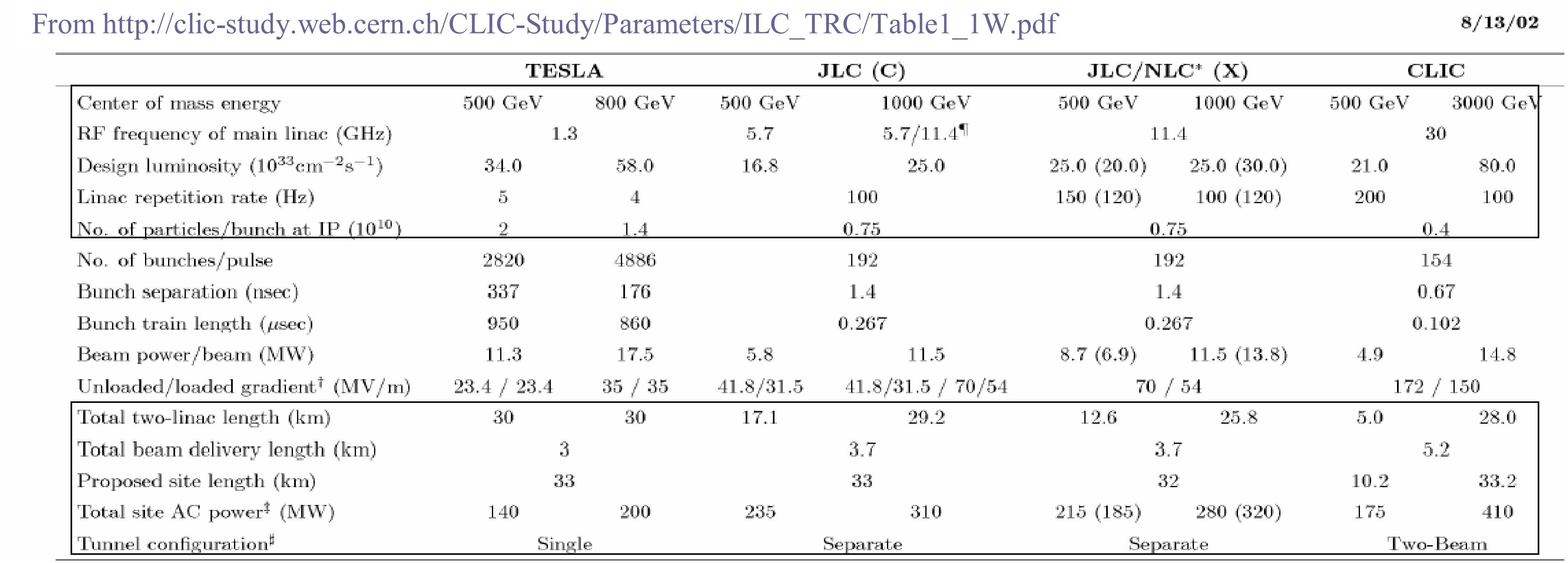
CLIC - Compact Linear Collider – 3 TeV



From http://clic-study.web.cern.ch/CLIC-Study/Layout/OverallCLIC3.html

Linear collider comparisons

From http://clic-study.web.cern.ch/CLIC-Study/Parameters/ILC_TRC/Table1_1W.pdf



8/13/02

	TESLA		JLC (C)		JLC/NLC* (X)		CLIC	
Center of mass energy	500 GeV	800 GeV	500 GeV	1000 GeV	500 GeV	1000 GeV	500 GeV	3000 GeV
RF frequency of main linac (GHz)	1.3		5.7	5.7/11.4¶	11.4		30	
Design luminosity $(10^{33}\mathrm{cm}^{-2}\mathrm{s}^{-1})$	34.0	58.0	16.8	25.0	25.0 (20.0)	25.0 (30.0)	21.0	80.0
Linac repetition rate (Hz)	5	4	100		150 (120)	100 (120)	200	100
No. of particles/bunch at IP (10^{10})	2	1.4	0.75		0.75		0.4	
No. of bunches/pulse	2820	4886	192		192		154	
Bunch separation (nsec)	337	176	1.4		1.4		0.67	
Bunch train length (μsec)	950	860	0.267		0.267		0.102	
Beam power/beam (MW)	11.3	17.5	5.8	11.5	8.7 (6.9)	11.5 (13.8)	4.9	14.8
Unloaded/loaded gradient† (MV/m)	23.4 / 23.4	35 / 35	41.8/31.5	41.8/31.5 / 70/54	70 / 54		172 / 150	
Total two-linac length (km)	30	30	17.1	29.2	12.6	25.8	5.0	28.0
Total beam delivery length (km)	3		3.7		3.7		5.2	
Proposed site length (km)	33		33		32		10.2	33.2
Total site AC power‡ (MW)	140	200	235	310	215 (185)	280 (320)	175	410
Tunnel configuration$^\sharp$	Single		Separate		Separate		Two-Beam	

	Tesla	NLC
selling features	long pulse	high grad
	low freq	expansion
	reduced wake fields	
	ground motion	
expansion paths	double RF	
	2 deg K	
	electro polish	

flat beam development @ A0 may eliminate 1 damping ring @ Tesla

Gamma-gamma collider

(taken from Jeff Gronberg, LLNL, Fermilab Line drive series
Mar. 15, 2001 Gamma-Gamma Colliders)

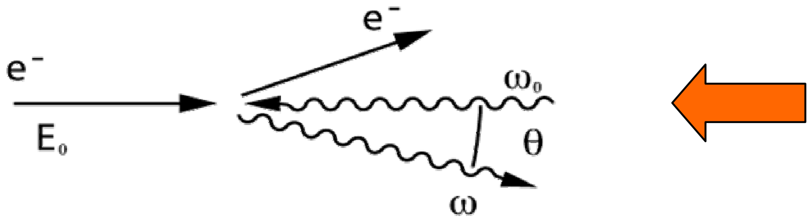
Proposed by Ginzburg et al. (1982) for producing a photon collider

Collide a high power laser pulse with an electron beam to produce a high energy photon beam

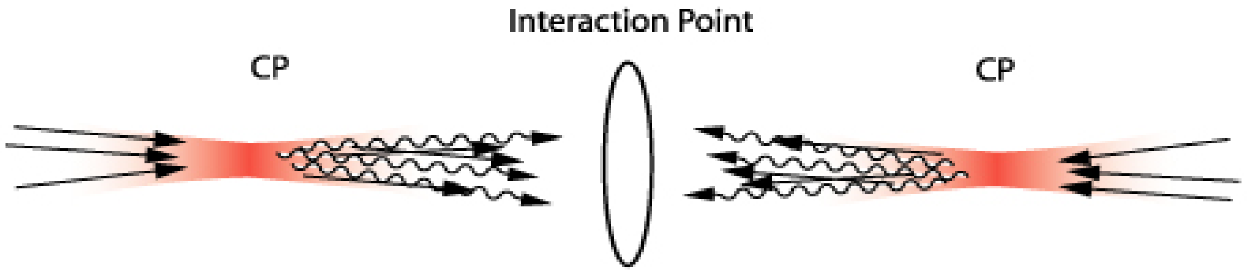
- laser: 1 J, 1.8 ps FWHM, 1 micron, > 1 TW, 10 KW av

Two body process

- Correlation between outgoing photon angle and energy (1/γ)
- Maximum energy when the photon is co-linear with the incoming electron (about 80% of e)



Laser 10^9 photons/e



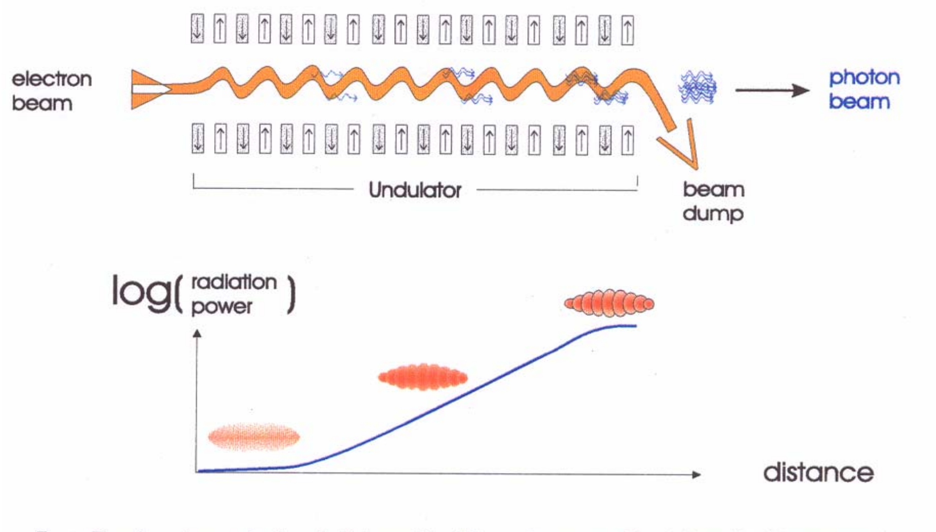
Free electron laser

SASE-self amplified spontaneous emission

first proposed at SLAC

Brilliance is 10^8 times current light sources, 1 Å x-rays, pulse length of 100 fs

TTF demonstrated SASE @ 80-180 nm



Free Electron Laser in the Self Amplified Spontaneous Emission (SASE) mode

Process: small xsec, high current e beam synchrotron radiates in undulator. For correct energy, undulator period get resonance in longitudinal charge density modulation

-micro bunching. Number of photons grows exponentially

From Tesla DR 3.6 The X-ray Free Electron Laser (XFEL) I-37

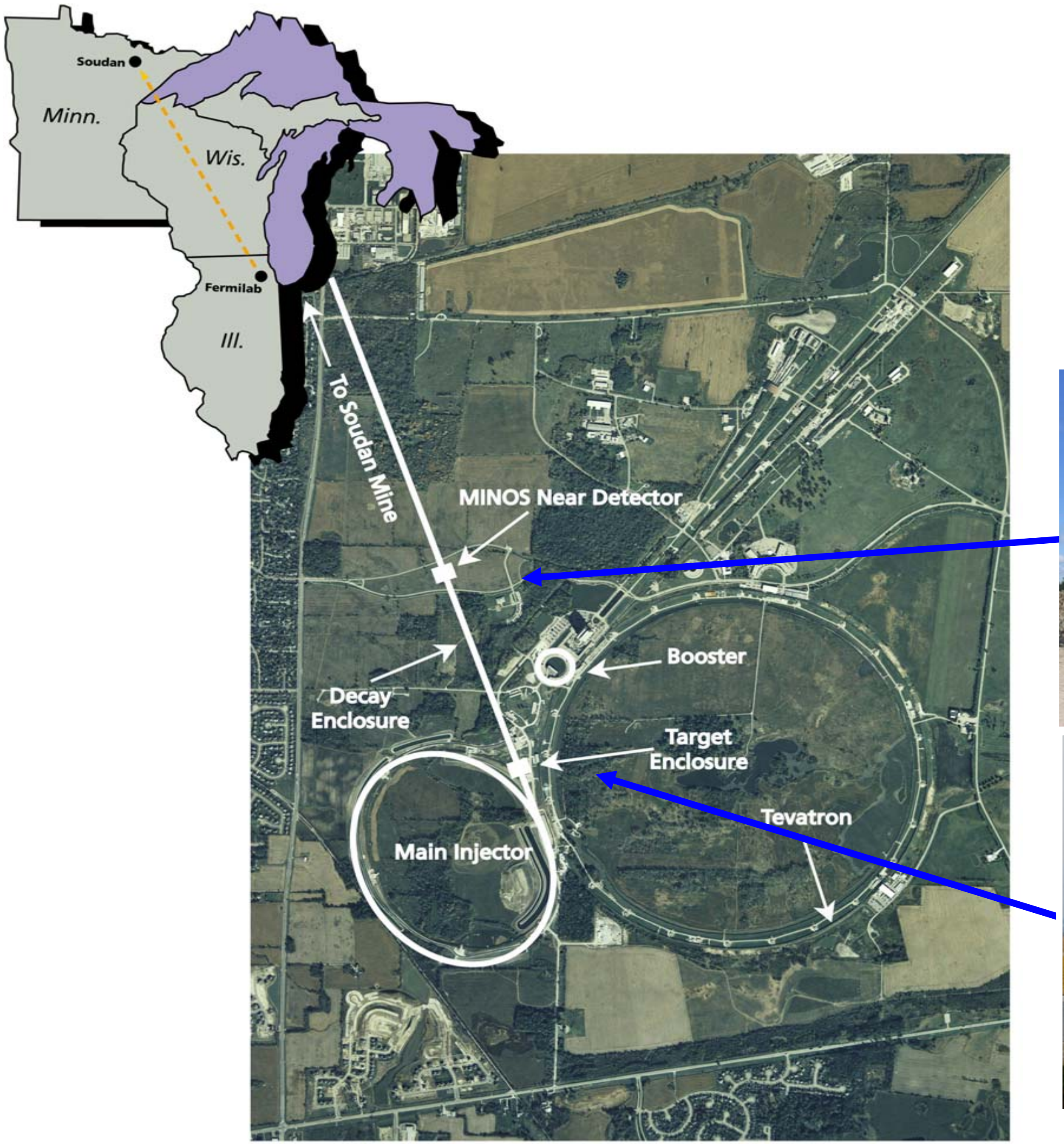
Mid range possibility - hot neutrino facilities

Conventional beams

Neutrino factories

Reactors-not accelerators

NUMI –
neutrinos at the Main Injector



FERMILAB #98-1321D

The NUMI project

120 GeV Protons from Fermilab Main Injector

10μs pulse, every 1.9s

Proton Intensity:

- 4×10^{13} protons/pulse design
- 2.5×10^{13} p/p expected at startup

Hadrons focused with 2 horns

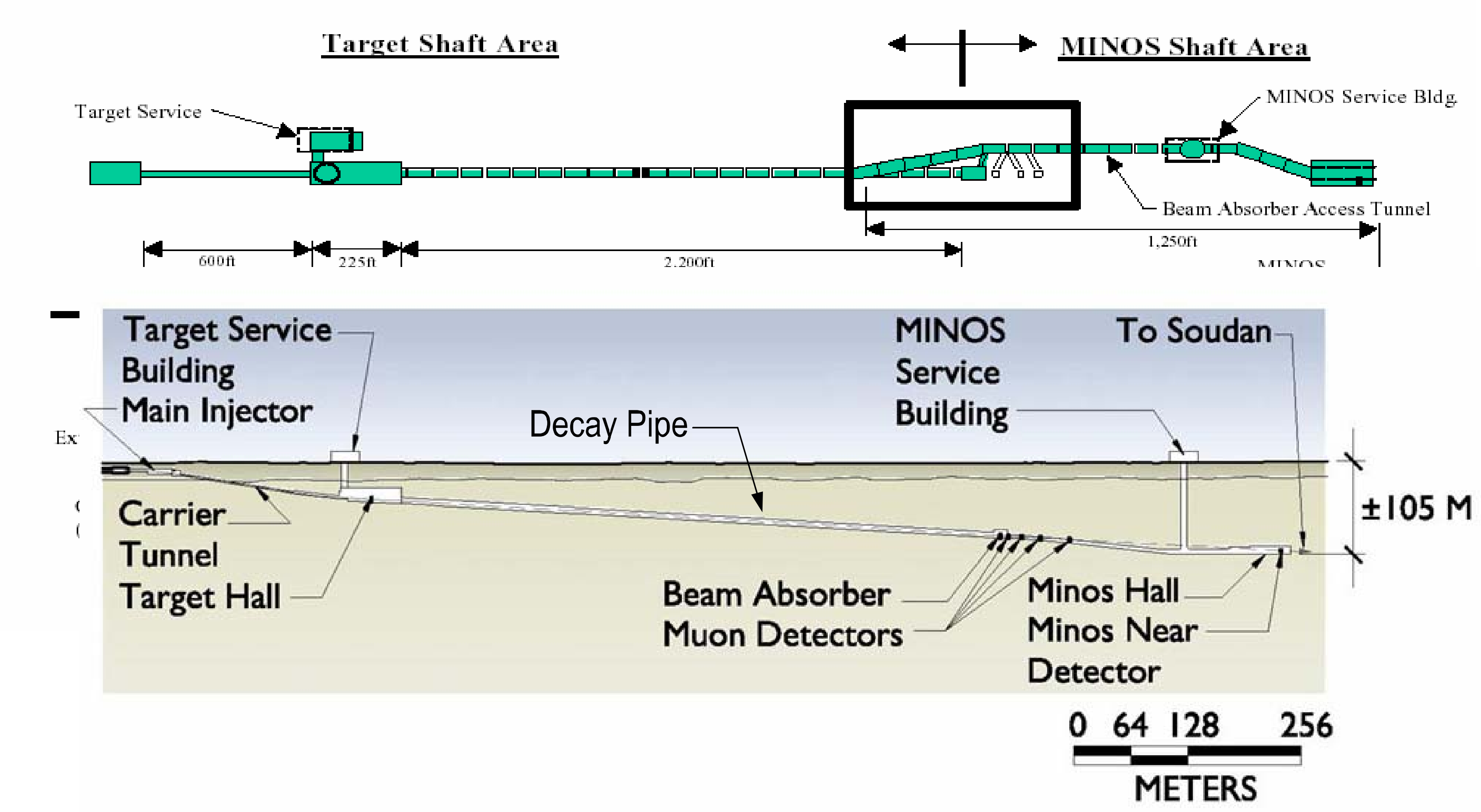
- Select beam energy spectrum by adjusting horn and target positions

Project will be complete/ commissioning starts Dec. 2004

0.2 MW first year

0.4 MW design

NUMI – layout


Target Shaft Area
MINOS Shaft Area
Target Service
MINOS Service Bldg.
Beam Absorber Access Tunnel
600ft
225ft
2,200ft
1,250ft
Target Service Building
Main Injector
Decay Pipe
MINOS Service Building
To Soudan
±105 M
Carrier Tunnel
Target Hall
Beam Absorber
Muon Detectors
Minos Hall
Minos Near Detector
0 64 128 256
METERS

NUMI - construction

Target Hall

Decay Pipe Endcap at Absorber Hall

Some neutrino beam naming jargon

NUMI	0.4 MW
Superbeam	2 MW
Neutrino factory	power about like superbeam more flexible on unlike sign suppression can do ν_e
Beta-beam	neutrinos via radioactive nuclei complicated

Going to superbeam
J. Hylen

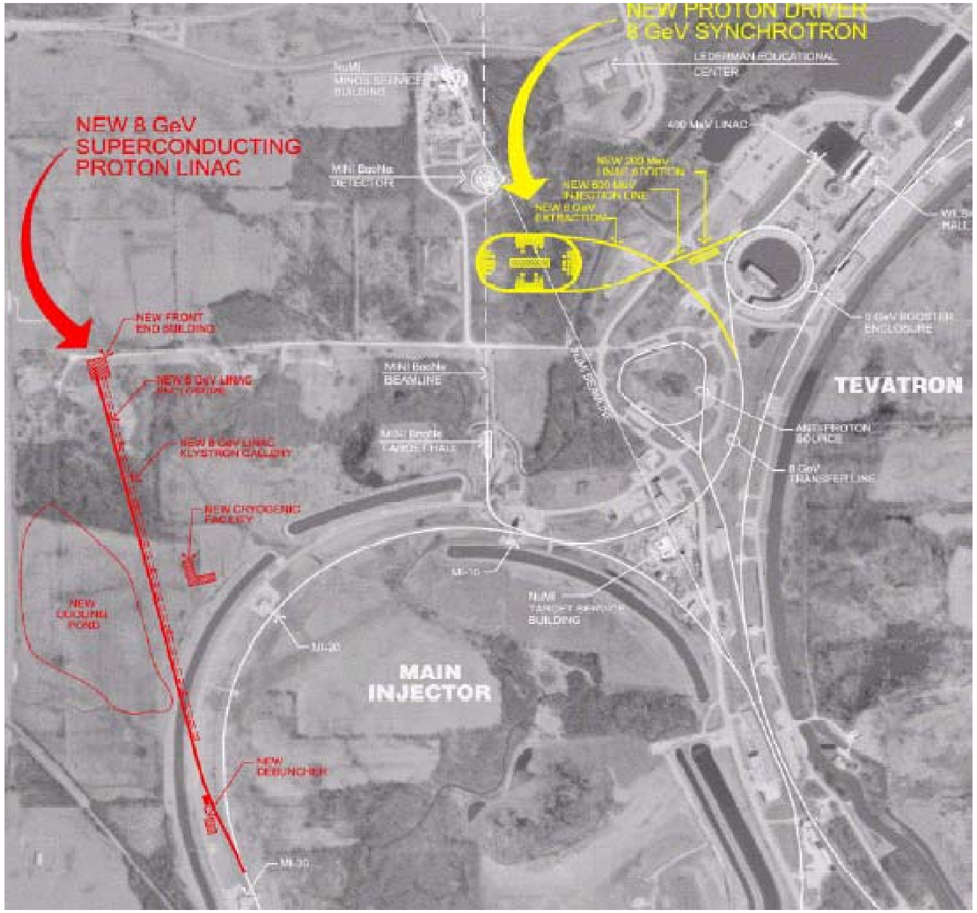
Difficulty of handling 2 MW instead of 0.4 MW depends significantly on:

- Proton beam energy still 120 GeV? (windows more problematic if lower)
- Increase repetition rate? (more cooling/electrical power for magnets)
- Increase protons per spill? (more stress on target, windows, horn)

General issues with higher beam power:

- Getting the average beam heating load out
- Average thermal stress limit
- Radiation safety
  - *Groundwater Protection*
  - *Airborne Activation*
  - *Prompt Radiation*
  - *Residual Activation*
- Radiation damage lifetime of materials
- Thermal shock
- Mis-alignment from thermal expansion
- Ionization leakage current

Possible Fermilab proton drivers



SYNCHROTRON (yellow)

Sited West of the existing booster

Re-uses existing linac enclosure

8 GeV LINAC (red)

Baseline Site injects at MI-30

straight section

Others possible

http://www.fnal.gov/orgs/fermilab_users_org/users_mtg/2004/foster.pdf0

Fermilab 8 GeV Superconducting Linac

New idea incorporating concepts from both the Spallation Neutron Source (SNS) and Tesla.

Copy SNS Linac up to 1.3 GeV

Use Tesla cryomodules from 1.3 to 8 GeV

H^- injection at 8 GeV in Main Injector

2 MW beam power at BOTH 8 GeV and 120 GeV

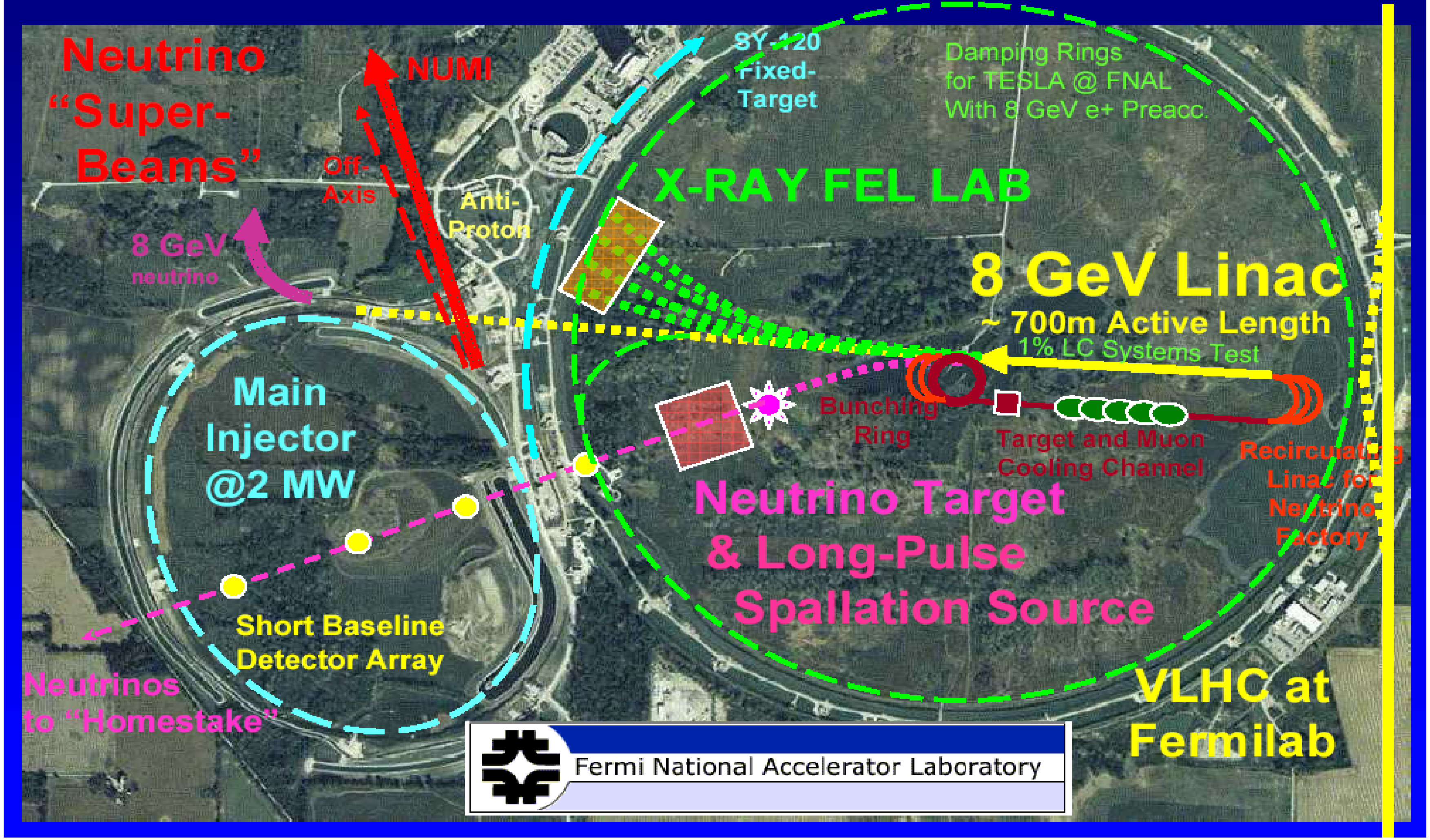
Small emittances so that there are small losses in Main Injector

A draft design study exist. Cost comparable to Main Injector.

http://www.fnal.gov/orgs/fermilab_users_org/users_mtg/2004/foster.pdf0

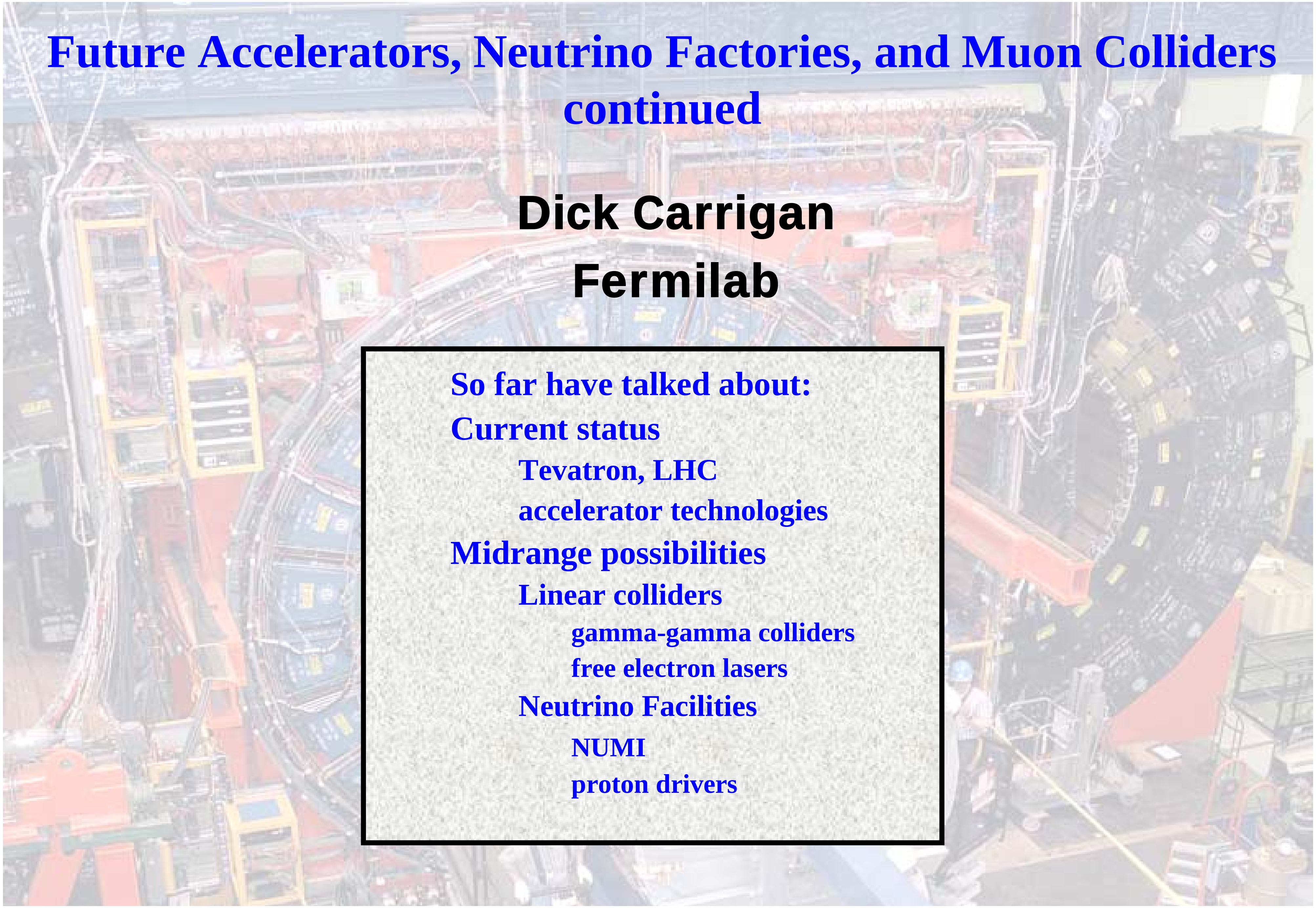
8 GeV Superconducting Linac

With X-Ray FEL, 8 GeV Neutrino & Spallation Sources, LC and Neutrino Factory



http://www.fnal.gov/orgs/fermilab_users_org/users_mtg/2004/foster.pdf0

Questions?



Future Accelerators, Neutrino Factories, and Muon Colliders continued

Dick Carrigan

Fermilab

So far have talked about:

- Current status
  - Tevatron, LHC
  - accelerator technologies
- Midrange possibilities
  - Linear colliders
    - gamma-gamma colliders
    - free electron lasers
  - Neutrino Facilities
    - NUMI
    - proton drivers

Mid range possibility muon collider

Muon storage ring-old concept

  recent BNL result for g-2

physics and Higgs

  $\sigma_H \sim (m_\mu/m_e)^2$

problem-collecting the muons

muons equal neutrinos-gave rise to idea of neutrino factories

Muon collider-concept

Produce pions with proton accelerator

pions decay: $\pi \rightarrow \mu + \overline{\nu}$ 30 MeV/c

muons decay: $\mu \rightarrow e + \nu + \overline{\nu}$ $\tau = 2.2\ \mu s$

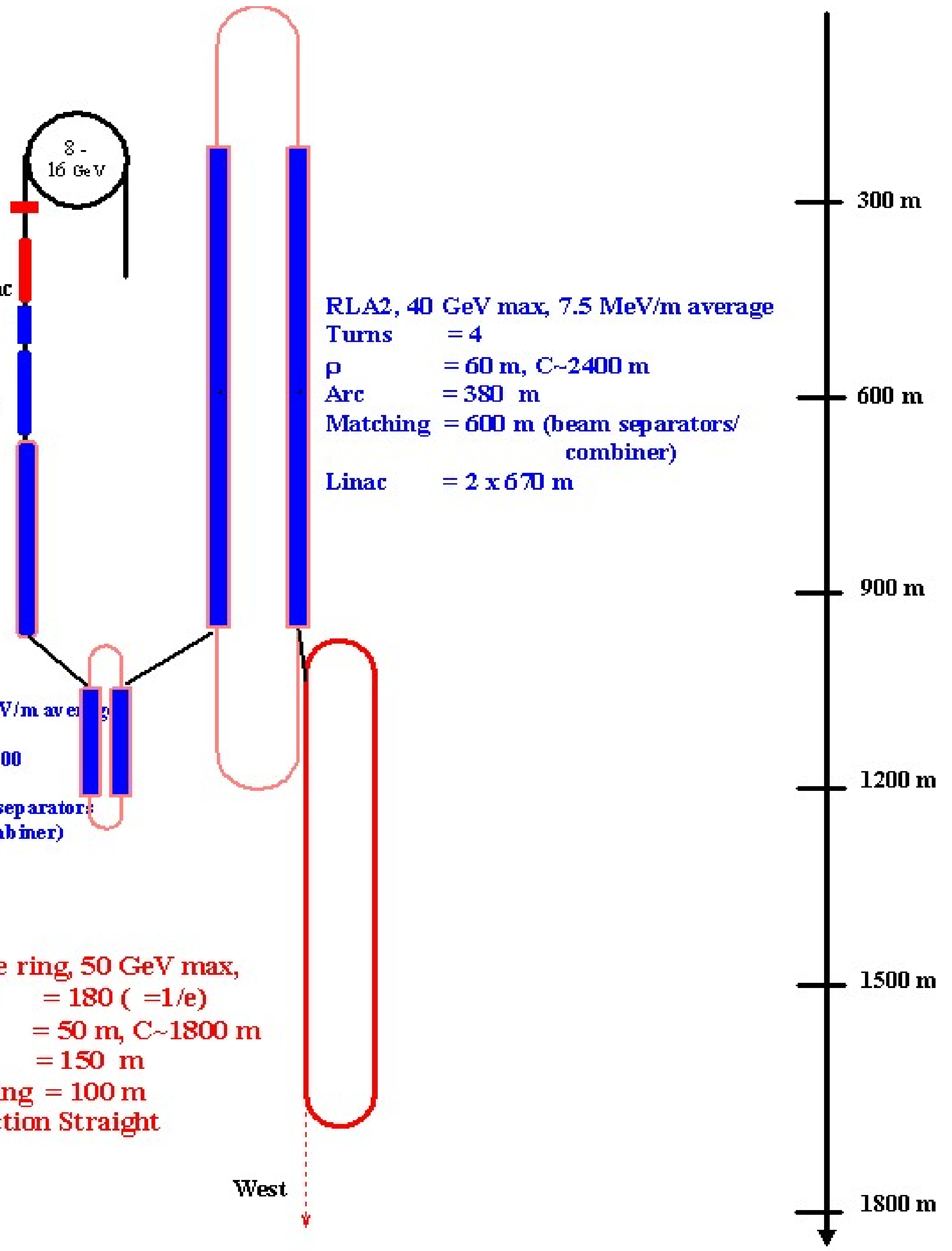
focus pions, muons-need a lens

cool muons-ionization cooling

6 dimensional phase space

accelerate very fast

Mid range possibility neutrino factories



Proton Driver + Linac

Target Station
50 m long drift

100 m long Induct. Linac
60 m long bunching

140 m long cooling
1.6 GeV, 200 MHz linac

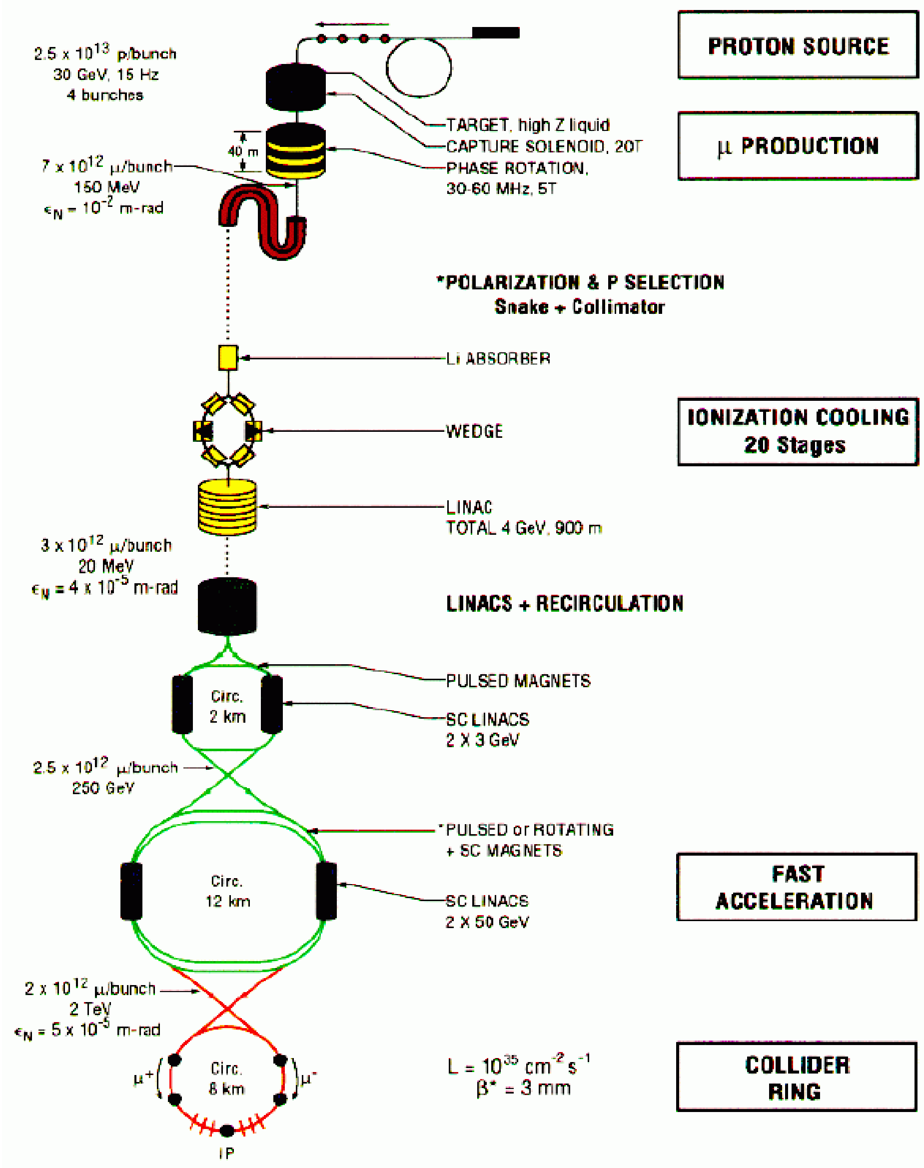
>3 GeV linac
2 GeV of acceleration

RLA2, 40 GeV max, 7.5 MeV/m average
Turns = 4
ρ = 60 m, C~2400 m
Arc = 380 m
Matching = 600 m (beam separators/ combiner)
Linac = 2 x 670 m

RLA2, 8 GeV max, 7.5 MeV/m average
Turns = 4
ρ = 25 m, C~800-900
Arc = 150 m
Matching = 200 m (beam separators /combiner)
Linac = 2 x 135 m

Storage ring, 50 GeV max,
Turns = 180 (=1/e)
ρ = 50 m, C~1800 m
Arc = 150 m
Matching = 100 m
Production Straight

Muon collider schematic (taken from Bruce King-BNL, 4th International Conference on the Physics Potential and Development of mu+mu- Colliders, San Fransisco, 1997.)



Very intense

Large aperture

Six degrees of
freedom
Does it work?

Very fast,
large aperture

Mid-range possibility
Very large hadron collider

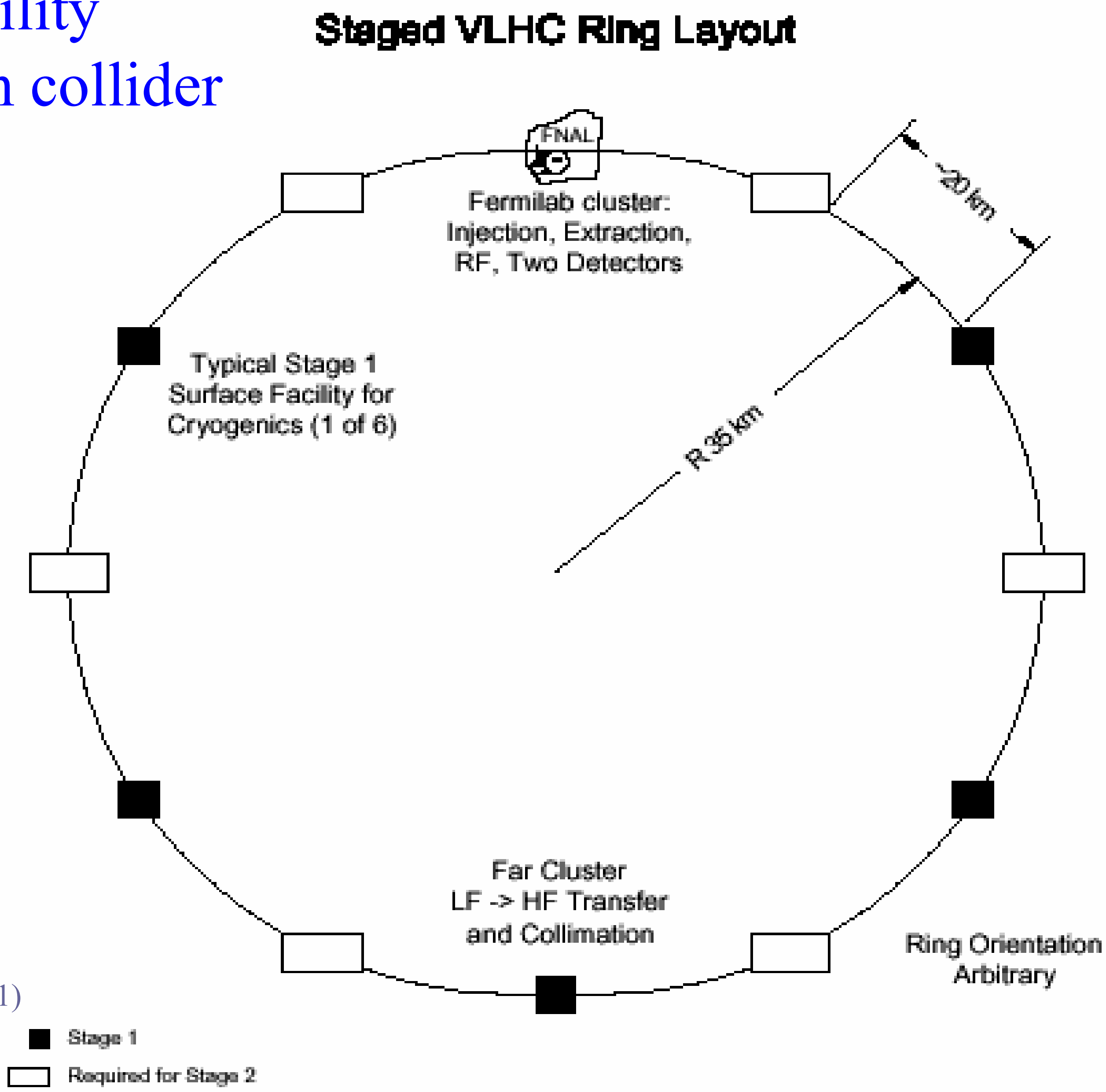
233 km circumference

Two stages:

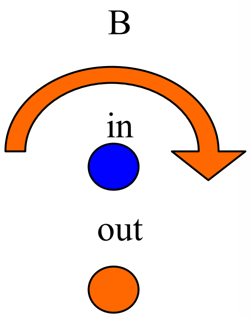
super ferric-20 TeV/beam

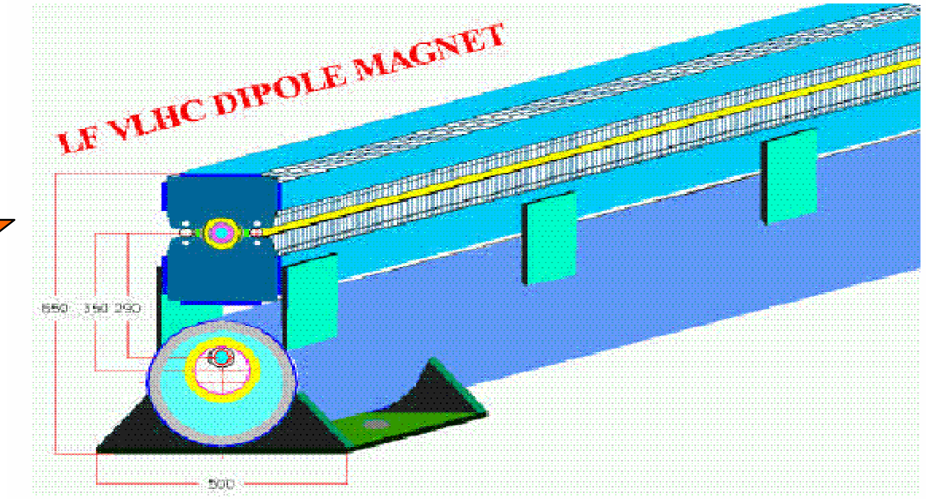
high field-87.5 TeV/beam

(from VLHC design report-2001)



VLHC super ferric magnet





Superconducting coil in center energizes both fields

2 cm gap, 2T

return loop is below

(from VLHC design report-2001)

Accelerator status recapitulation

- this decade-Tevatron, LHC
  - NUMI
- next decade-ambitious future
  - linear collider
  - Neutrino factory?
    - muon factory?
  - VLHC?
- 2020
  - New technology, need a vision

Visionary possibilities for acceleration

Would like much higher accelerating gradients

Two thoughts:

Lasers

R. Palmer, Particle Accelerators V11, 81 (1980). Recent progress Kimura et al. PRL **92**, 054801 (2004). See also LEAP at Stanford (Colby)

Plasmas

Tajima and Dawson PRL **43**, 267 (1979)

E. Esarey, et al., IEEE Trans. On Plasma Sci, **24**, 252 (1996).

J. Dawson, Scientific American March, 1989 (p. 54)

Lasers

basic laser challenge

- good news: can get very high fields
- bad news: vectors transverse to particle direction

ways to defeat

- gratings, maybe boundary conditions, special modes

R. Palmer, Particle Accelerators 11, 81 (80)

Inverse free electron laser IFEL-next transparency

Cascading laser stages

[from W. Kimura et al, PRL 86, 4041 (2001)]

Inverse free electron laser (IFEL)

electrons oscillate in undulator and absorb energy from laser

Gradients not on a scale with plasma accelerators

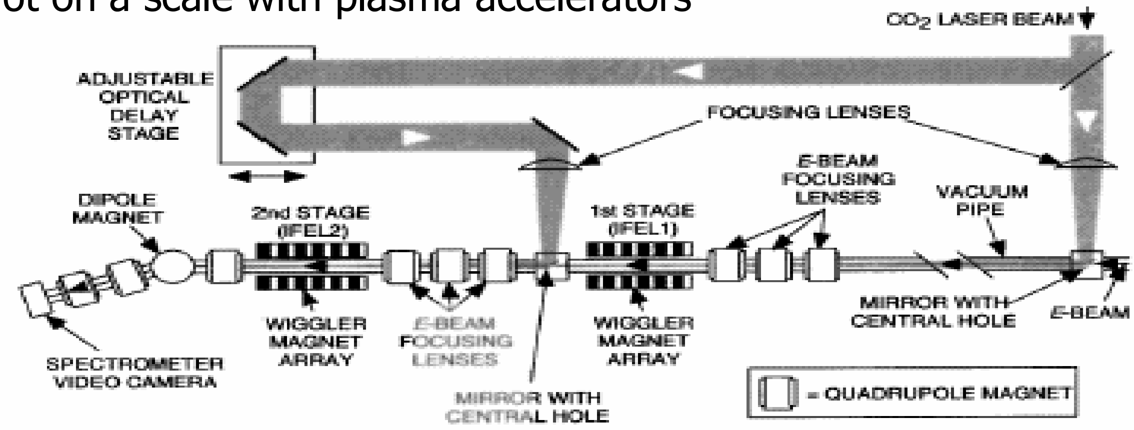


FIG. 1. Schematic layout for the STELLA experiment. For size reference, the distance separating the two IFELs is 2.3 m and the laser beams enter the beam line ≈6 m apart.

Require fs micro bunches, very good timing

24 MW first stage, 300 MW second

This demonstrated rephasing, not acceleration

Plasma wake field acceleration

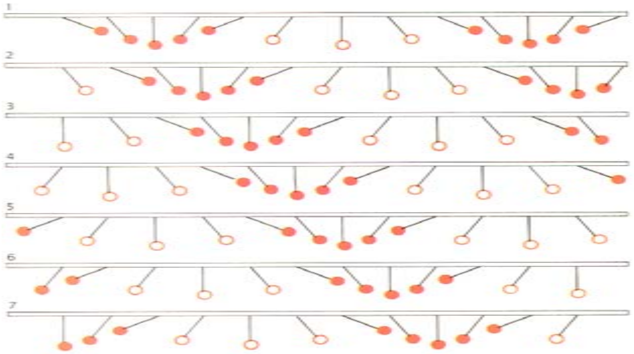
Photo S. Carrigan

$G = 0.96(n_0)^{1/2}$ (V/cm) n_0 is electron density

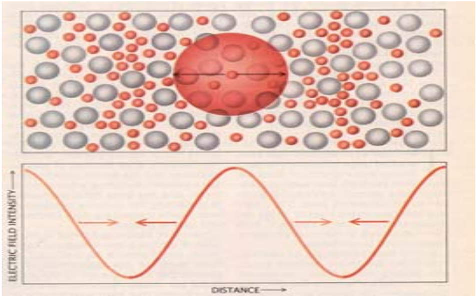
RF cavity	0.0005 GV/cm
gaseous plasma	1 GV/cm

Plasma model

(from Lawson, Scientific American-1989)

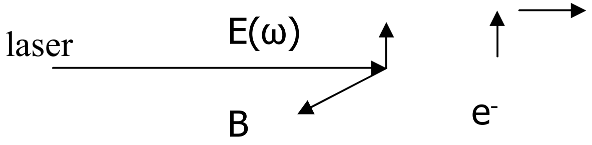


Pendulum cluster moves to the right



Plasma snapshot: red plasma electrons cluster and make field. Electrons in red ball are trapped.

Creating a plasma wave with a laser



Ponderomotive force on electron

Generated field is:

$E = m_e c\omega_p/e$ (e.g. sin dist of charge)

$\omega_p = (4\pi n_0 e^2/m_e)^{1/2}$ plasma freq

plasma wave has a phase velocity

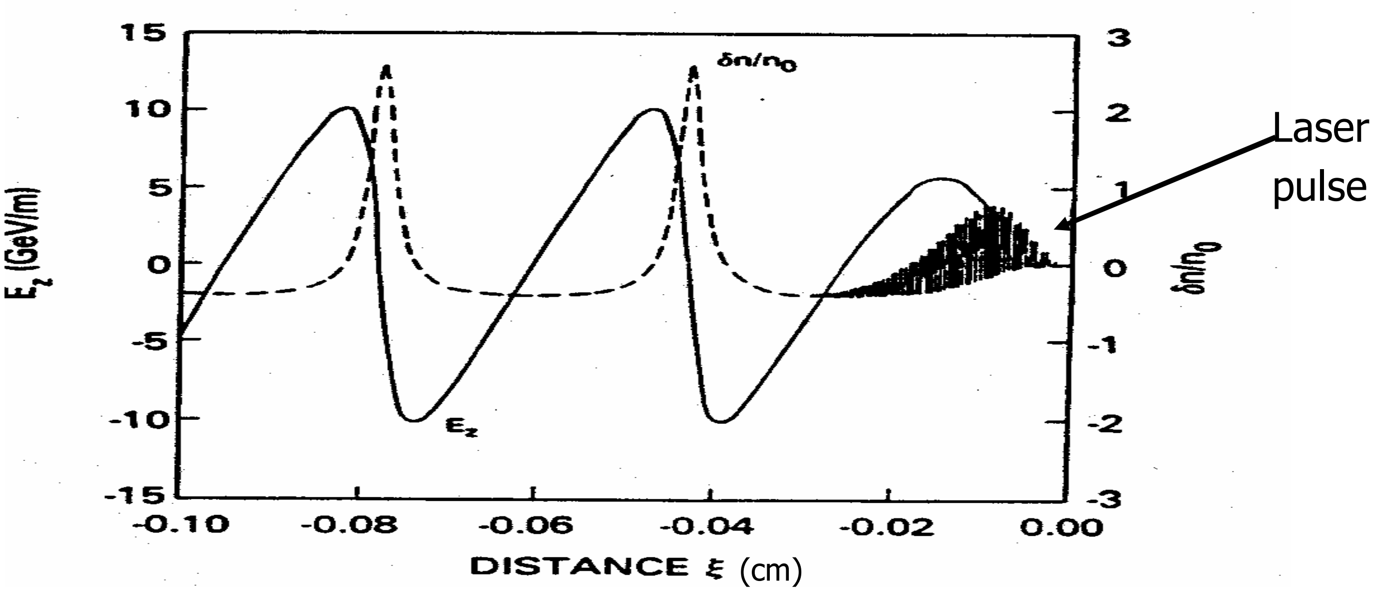
$v_p = c(1-\omega_p^2/\omega^2)^{1/2}$

wake generated best when photon packet is half wavelength of plasma

find $\gamma^{max} = 2\ \omega^2/\omega_p^2$

acceleration length: smallest of dephasing length, pump depletion length, or depth of field (optical channel helps)

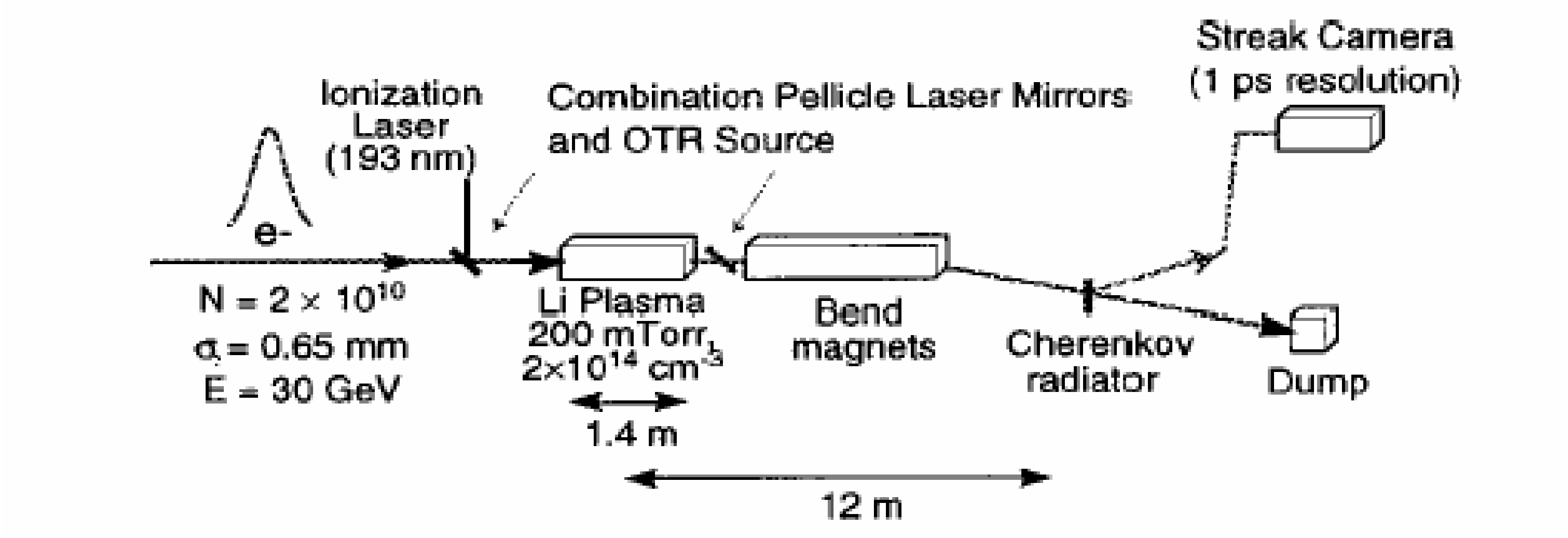
Characteristic field strengths



highly relativistic laser driven plasma. Laser pulse length is .03 cm, pulse moves to right, fast oscillations are laser freq. Density (n_0) is 10^{16}/cm^3. Moderate case would be more sinusoidal.)

(from Sprangle, et al.)

A wakefield accelerator - E157 at SLAC



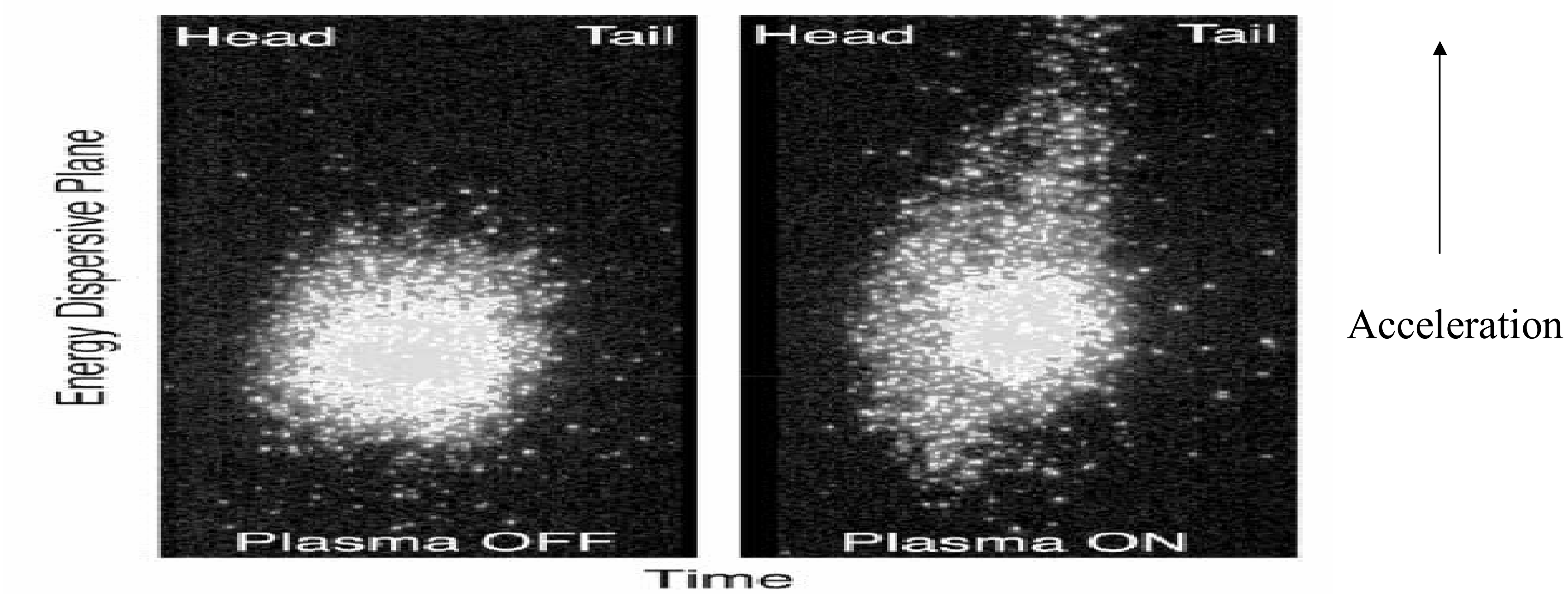
Head of beam generates plasma wakefield,

tail is accelerated by 80 MeV. Also do e^+ - E162.

(E-164 later version , n_e O($3*10^{15}$), 100 micron bunches
- see 2003 Particle Acc. Conf, p. 1530)

M. Hogan Phys. Plasmas 7, 2241 (2000)

Results from SLAC E-157



Barov and Rosenzweig (UCLA) see similar results at Fermilab.
100 MeV/m using A0 14 MeV photoinjector. 6-8 nC, $n_e \sim 10^{14}$/cc.

M. Hogan Phys. Plasmas 7, 2241 (2000). See also Muggli, et al. PRL **93**, 014802-1 (2004)

Bob Hofstadter
"The Atomic Accelerator" HEPL 560 (1968)

"To anyone who has carried out experiments with a large modern accelerator there always comes a moment when he wishes that a powerful spatial compression of his equipment could take place. If only the very large and massive pieces could fit in a small room!"

Hofstadter wanted a crystal accelerator!

A table top accelerator ("miniac")

- The first solid state accelerator
- use channeling for focus
- maybe an after-burner scheme
- excite atoms coherently with 1 keV-xray

Get out 1 keV/Å

- in 1 cm would get 100 GeV

Need an **x-ray laser** (1968)

Problem-transit time

Photo S. Carrigan

Plasma wake field acceleration – solid state

$G = 0.96(n_0)^{1/2}$ (V/cm) n_0 is electron density

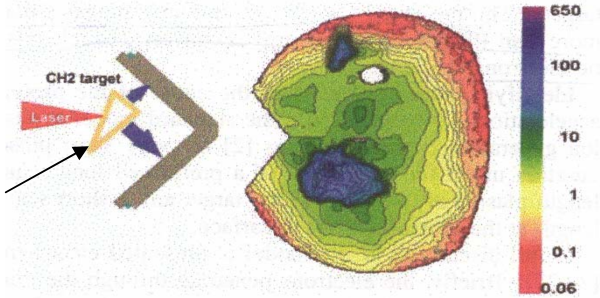
RF cavity	0.0005 GV/cm
gaseous plasma	1 GV/cm
solid state plasma	100 GV/cm

Pseudo solid state accelerators

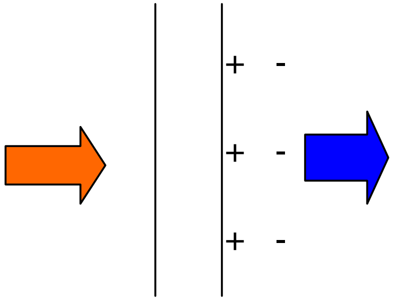
At least four groups see high energy ions, electrons from intense lasers hitting foils

Livermore PRL 85, 2945 (2000)
Michigan APL 78, 595 (2001)
Rutherford PRL 90, 064801 (2003) – discussion of mechanisms, target evolution
LULI PRL **85** 1654 (2002)

Livermore



wedge



$3*10^{20}$ W/cm^2, 1000 TW, 10^{13} proton beams with E to 58 MeV, electrons
protons can be focused by curving target

process: electrostatic fields produced by ponderomotively accelerated hot electrons act on protons from absorbed hydrocarbons rear side (downstream)

Basic Crystal Accelerator Concept

excite plasma wake field in solid with density a thousand times gas

use channeling to reduce energy loss, focus, and maybe even cool

Chen-Noble Tahoe (1996), p. 441

Positives

very high power, femtosec lasers

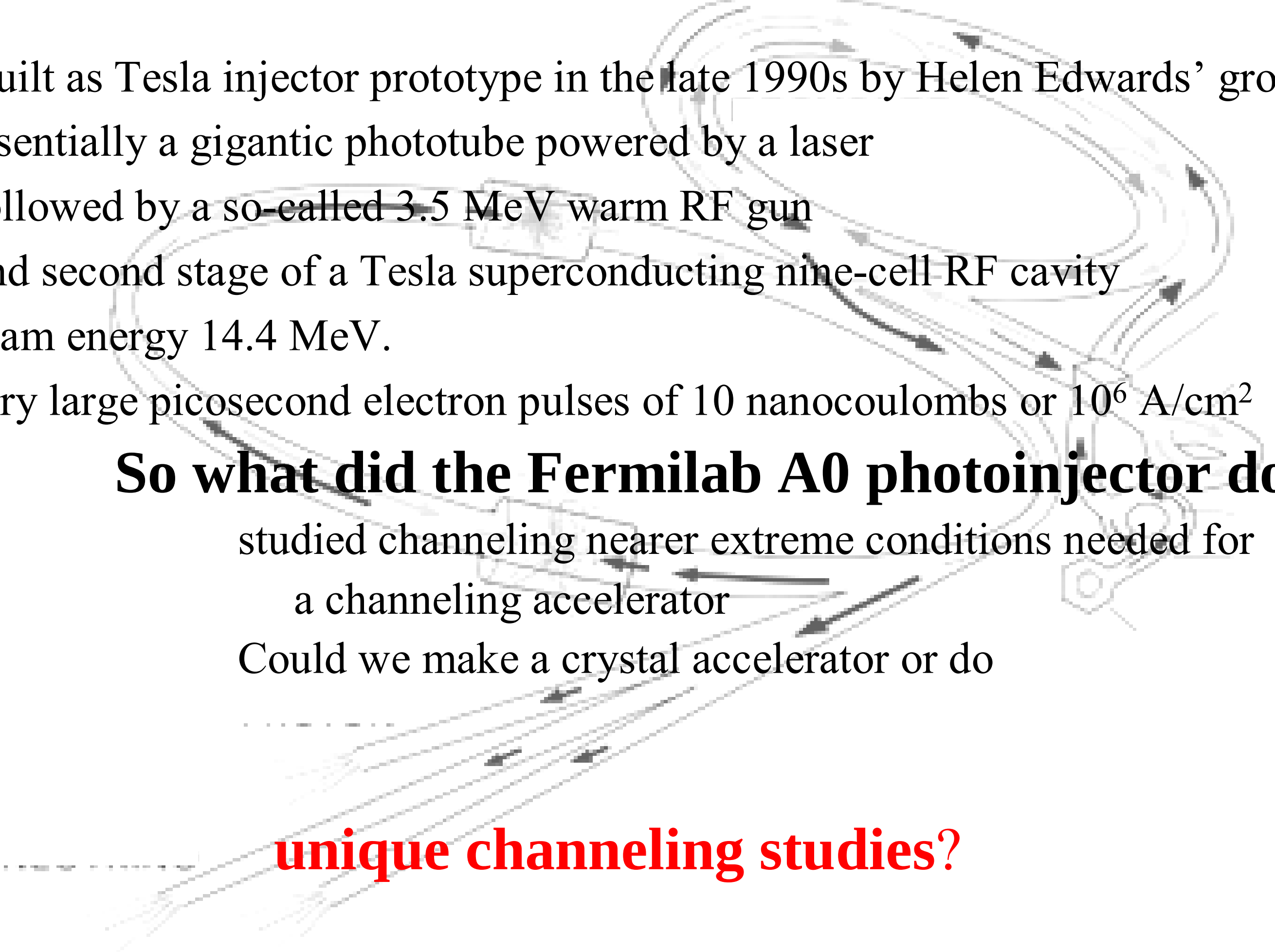
radiative damping (Huang, Ruth, Chen)

Big problems!

blow away material

dechanneling

The Fermilab A0 photoinjector



- built as Tesla injector prototype in the late 1990s by Helen Edwards' group
- essentially a gigantic phototube powered by a laser
  followed by a so-called 3.5 MeV warm RF gun
  and second stage of a Tesla superconducting nine-cell RF cavity
- beam energy 14.4 MeV.
- very large picosecond electron pulses of 10 nanocoulombs or 10^6 A/cm^2

So what did the Fermilab A0 photoinjector do?

studied channeling nearer extreme conditions needed for
a channeling accelerator
Could we make a crystal accelerator or do

unique channeling studies?

Crystal survivability?

Process

excite electronic plasma

tunnel ionization

partial or total lattice ionization

electronic plasma decay

via interband transitions

lifetime: (plasma frequency)-O(fs)

$$\omega_p = \left(4\pi n_0 e^2 / m_e\right)^{1/2}$$

excitation of phonons in lattice

crystal disorder, fracture, or vaporization

lattice dissociation via

plasmon absorption

lifetime: (ion plasma frequency)$^{-1}$

$$\omega_{pi} = (m_e / m_i)^{1/2} \omega_p$$

vaporization O(10-100 fs)

hydrodynamic heating O(1-10 ps) [Livermore]

Crystal destruction

ACCELERATION

G (gradient) proportional to $(n_0)^{1/2}$, P (power) prop to n_0

for G = 1 GeV/cm P = 10^5 J/cm^3

10^{19} W/cm^3

for O(10 fs) @ 1 GeV/cm

LASER

10^{11} W/gm

Belotshitkii & Kumakhov (1979)

or 10^6 a/cm^2 for particle beam

10^{12} W/cm^3 ns long pulses

10^{13} W/cm^3 Chen-Noble (1987)

fracture threshold

O(0.1 ns) ref 16

Skin depth < 0.1 mm

LATTICE IONIZED

10^{15}-10^{16} W/cm^2 Chen & Noble (1996)/laser

PARTICLE BEAM

10^{11} A/cm^2 Chen & Noble (1987) (crystal OK for 10 fs)

Situation for Fermilab A0 photoinjector

A0 RF GUN FOR COMPARISON

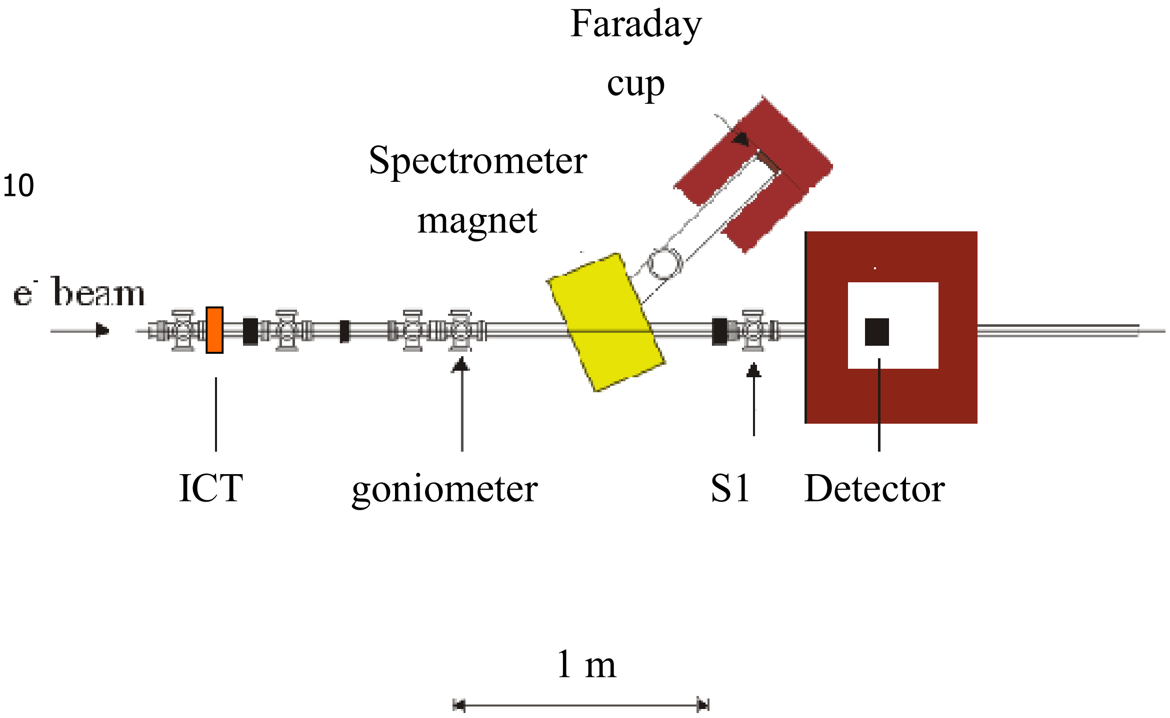
I/cm^2 = 10 nc/1 ps in 1 mm^2 or 10^6 A/cm^2 (OK driver @ 1GeV)

A0 LASER FOR COMPARISON

10 W/cm^3	slap ruptured (continuous, 10^{15}W/cm^3 for 10 fs)
10^9 W/cm^2	damage on lens
10^{18} W/cm^2	1 Joule on 10 μm spot in 1 ps (OK driver)

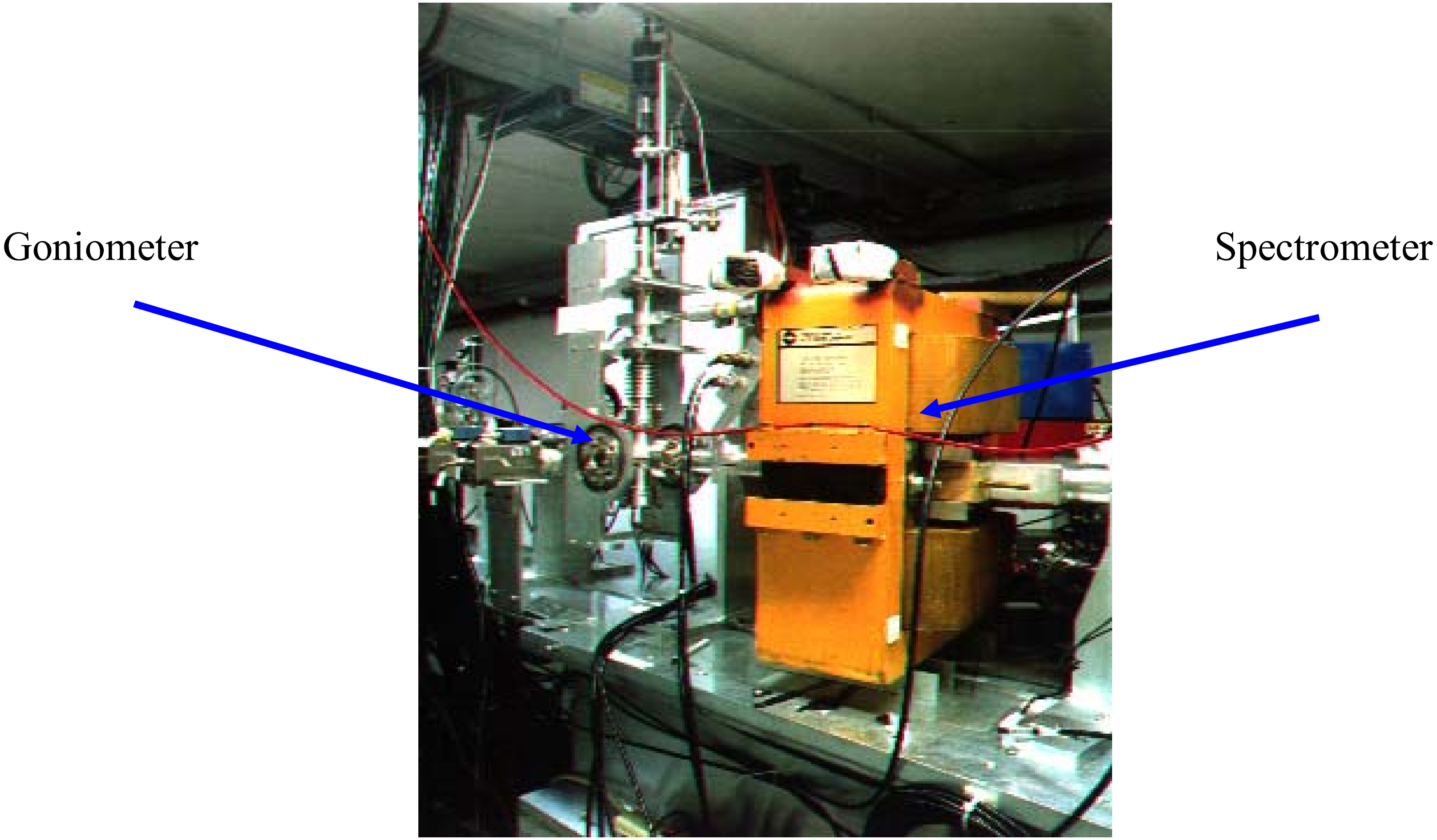
Fermilab A0 schematic layout

$N_e = 5*10^{10}$



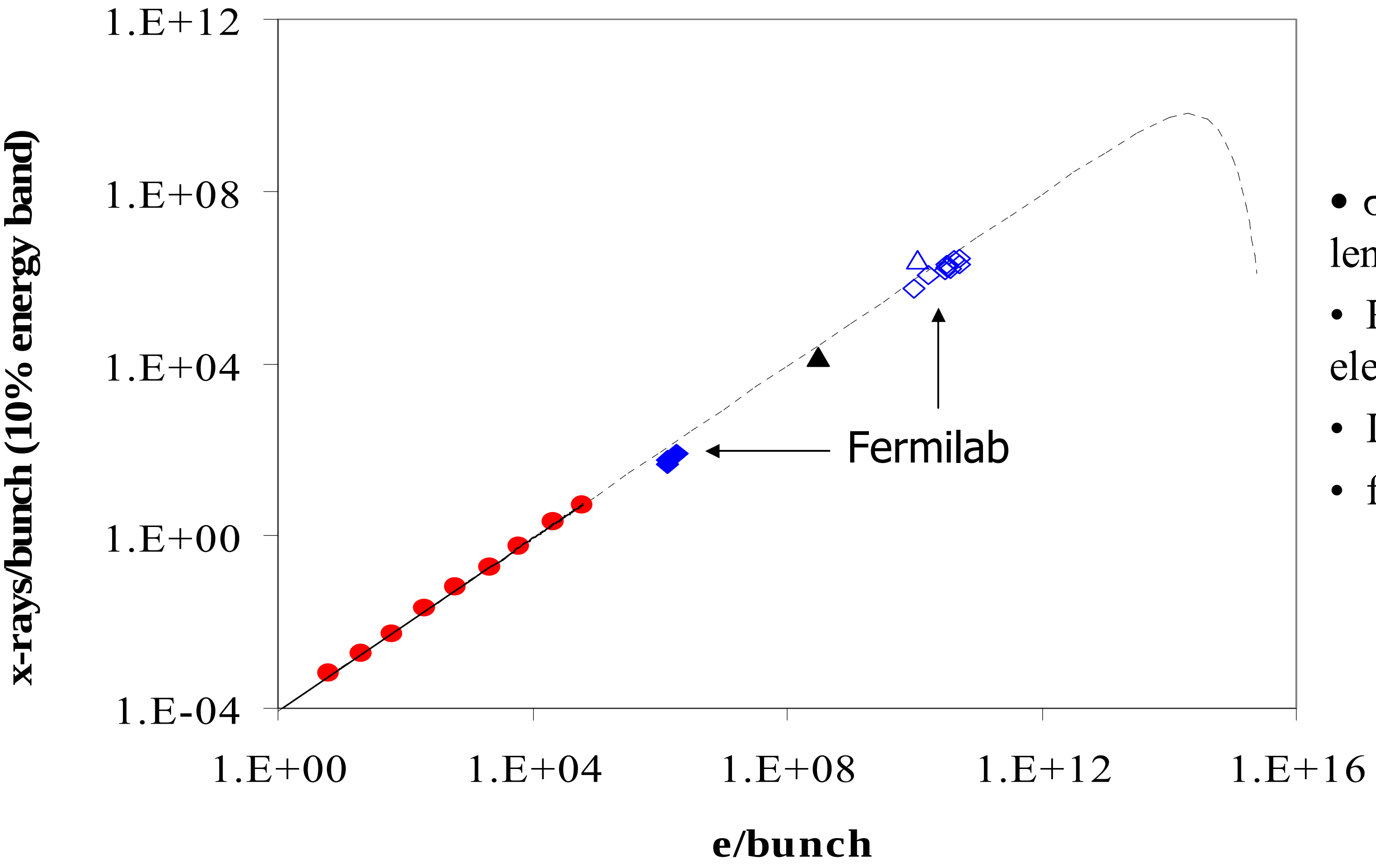
R. Carrigan, et al. Phys. Rev. A68, 062901 (2003)

A0 at the goniometer



10 nC peak, ε typically 10 mm*mrad, 10 ps

Summary of high charge measurements



- σ_b is O(0.5 mm), length = > 7 ps (σ)
- Peak n/cm^2 is 10^{13} electrons/cm^2
- I/cm^2 = 10^5 A/cm^2
- flat is not ruled out

The Future Beyond the Fermilab A0 Experiment

get into 10 fs regime

n_e 10^3 to 10^5 larger (small beam size important)

higher energy might be better for channeling, beam size

But new experimental geometry, channeling approaches needed

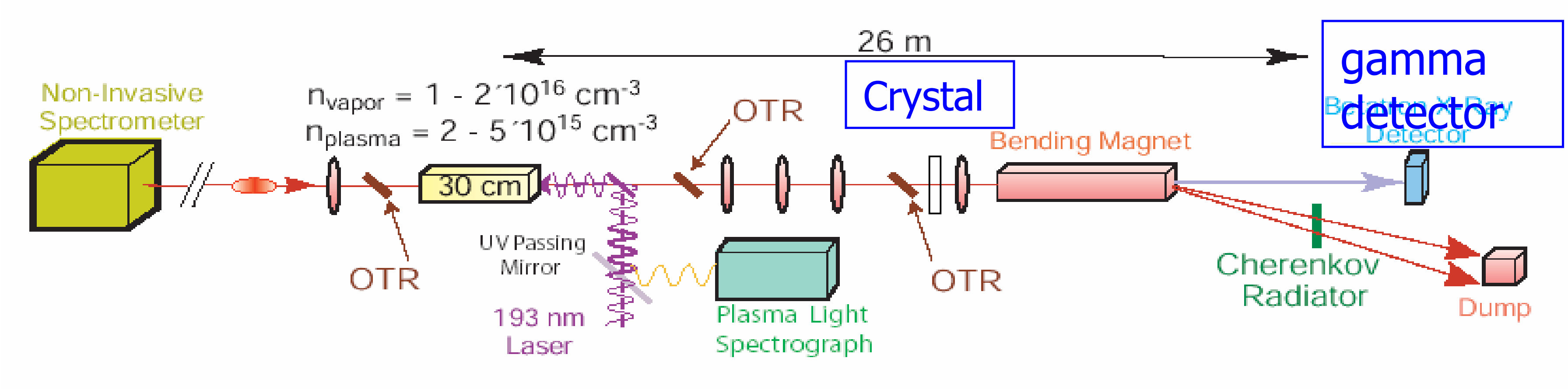
Possibilities:

SLAC E164 geometry for channeling radiation at 30 GeV

Livermore

Toronto – studying laser melting with sub picosec electron diffraction

Using SLAC E164 to study channeling



Add crystal, goniometer, x-ray det. (integrating). Now at FFTB (final foc TB) for big q.

Channeling radiation ala N. A. Filatova, Phys. Rev. Lett. **48**, 488 @ 12 GeV, (1982), K. Kirsebom, et al., NIMB **119**, 79 (96) @ 150 GeV.

Beam:

charge: $2*10^{10}$/bunch (< A0), size 25 μm.

time: 100 mm/c = 300 fs

I/cm^2: $50*10^6$ A/cm^2 (500 times better than A0)

This could take channeling measurements nearly to the plasma regime.

C. Barnes et al., Proc. 2003 Particle Acc. Conf. 1530 (03)

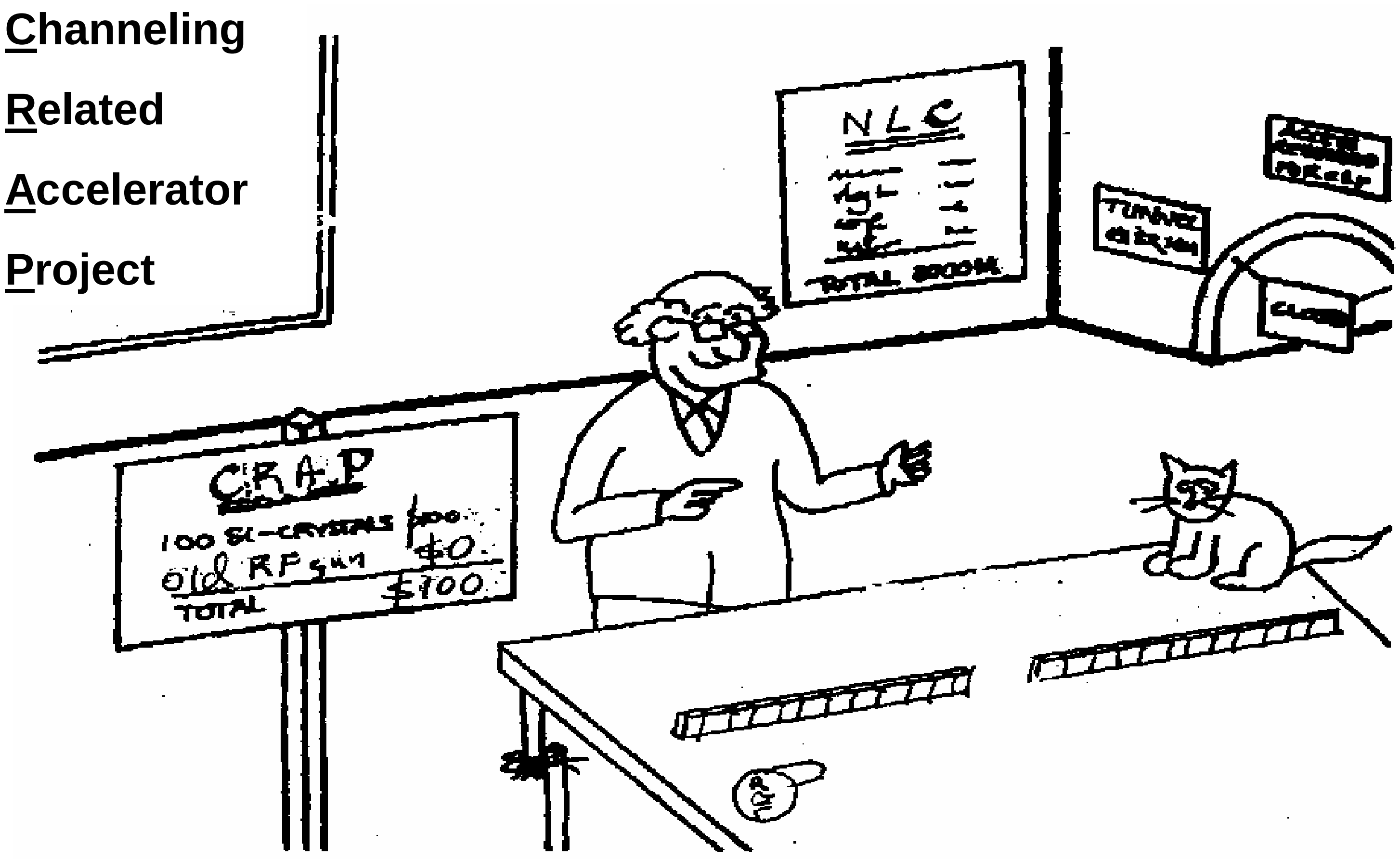
The Far Future?

Channeling

Related

Accelerator

Project



Summary

2001-2009

- Tevatron-completing a decade
  - has a proton driver been added?
- LHC-in operation for pp (15 yr future)

2010-2019

- linear collider completed somewhere, running underway
  - upgrade path?
- Neutrino factories?

2020-2029

- VLHC?
- Muon collider?
- Can exotic accelerators step up?

Questions?