LIMITS TO ACCELERATORS

FOR CIRCULAR MACHINES

PROTONS → B FIELD & RADIUS $\rho = \frac{p}{0.3B}$

LHC 8.4T SUPERCONDUCTING MAGNETS

↑

CLOSE TO LIMIT FOR
Nb_3Sn SUPERCONDUCTOR

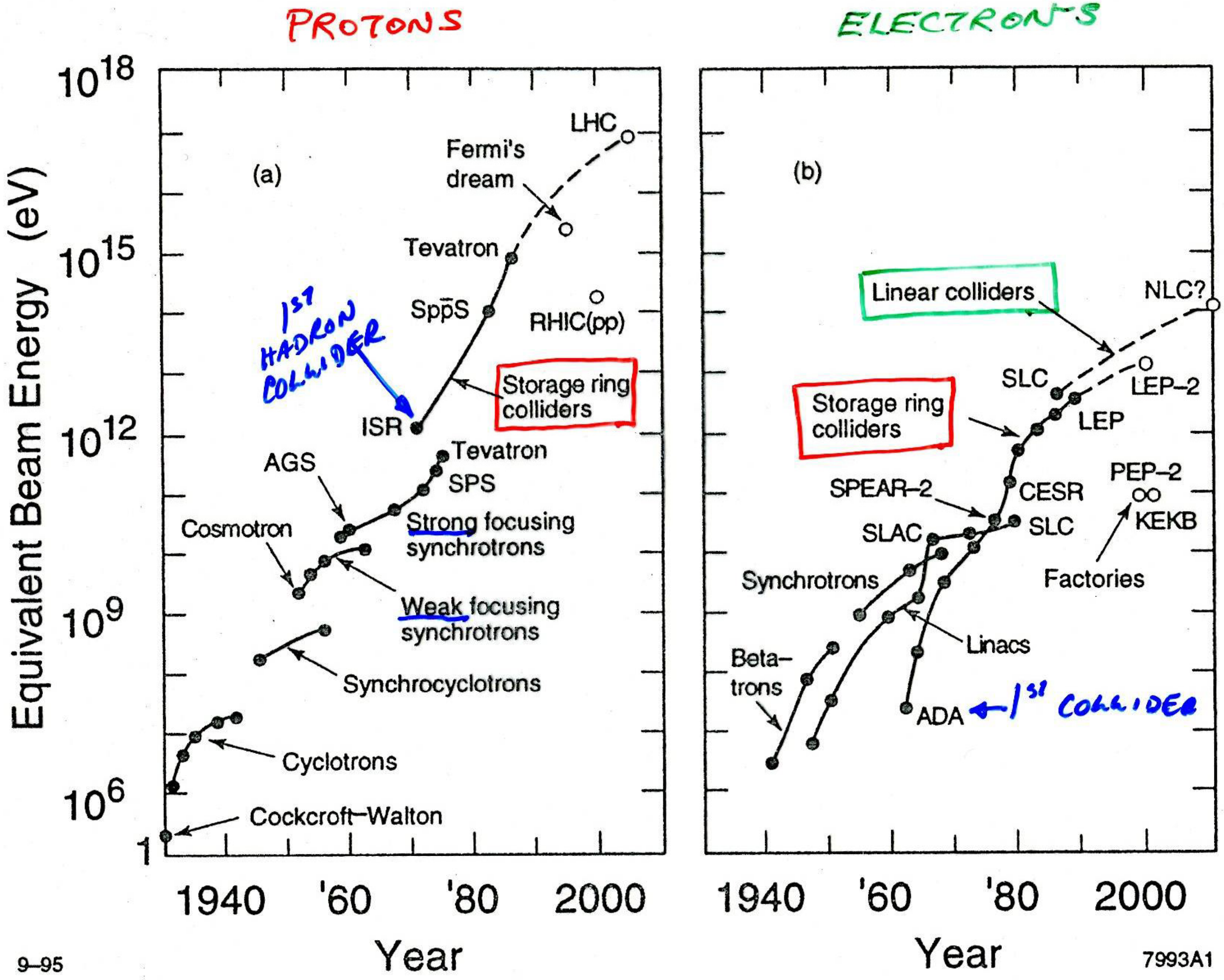
$R_{EFF} = 3km$
$CIRC = 27km$

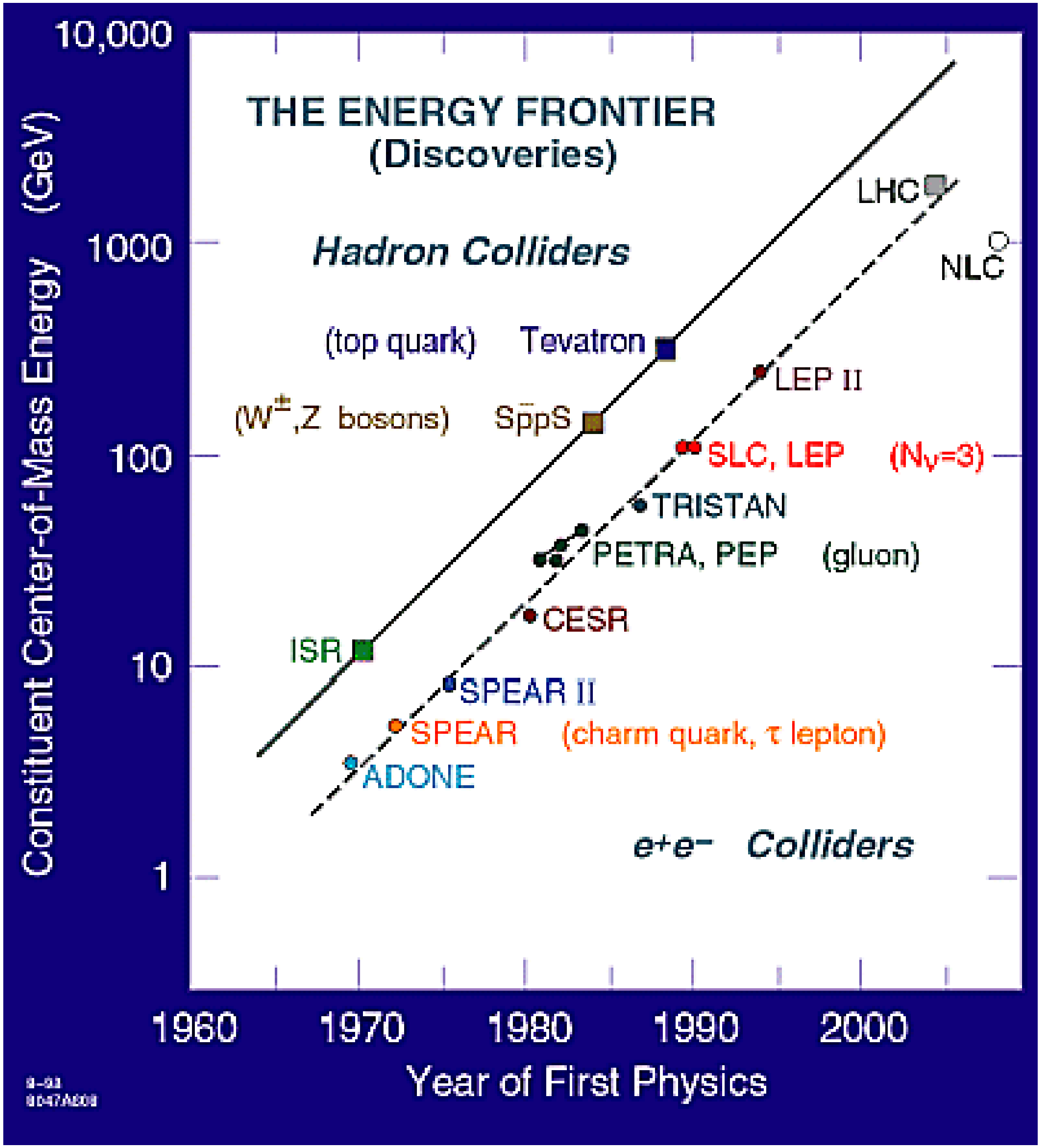
THERE ARE HIGHER FIELD MAGNETS UNDER DEVELOPMENT → MECHANICAL STRESS ?

ELECTRONS → LEP WAS AT SYNCHROTRON RADIATION LIMIT

SO WE SEEM CLOSE TO LIMIT FOR CONVENTIONAL CIRCULAR MACHINES.

LIVINGSTON PLOT




THE ENERGY FRONTIER
(Discoveries)
Hadron Colliders
e^+e^- Colliders
Constituent Center-of-Mass Energy (GeV)
10,000
1000
100
10
1
Year of First Physics
1960
1970
1980
1990
2000
LHC
NLC
(top quark)
Tevatron
LEP II
($W^\pm$,Z bosons)
S$\bar{p}$pS
SLC, LEP
(N_ν=3)
TRISTAN
PETRA, PEP
(gluon)
CESR
ISR
SPEAR II
SPEAR
(charm quark, τ lepton)
ADONE

LHC Prospects

[redacted] upgrading the machine

HIGH LUMINOSITY LHC

Two options presently discussed/studied

- Higher luminosity ~10^{35}cm^{-2} s^{-1} (SLHC) — 5×10^{34}
  - Needs changes in machine and particularly in the detectors
  - ⇒ Start change to SLHC mode some time ~~2012-2014~~ > 2020
  - ⇒ Collect ~3000 fb^{-1}/experiment in 3-4 years data taking.
- Higher energy?
  - LHC can reach $\sqrt{s}$ = 15 TeV with present magnets (9T field)
  - $\sqrt{s}$ of 28 (25) TeV needs ~17 (15) T magnets ⇒ R&D + MCHf needed

2016
~1.4×10^{34}

2017
2.06×10^{34}

Machine Upgrade in Stages

- Push LHC performance *without* new hardware
  - luminosity →2.3×10^{34} cm^{-2}s^{-1}, $\underbrace{E_b=7\rightarrow7.54\text{ TeV}}_{??}$
- LHC IR upgrade
  - replace low-β quadrupoles after ~7 years
    peak luminosity →4.6×10^{34} cm^{-2}s^{-1}
- LHC injector upgrade
  - peak luminosity →9.2×10^{34} cm^{-2}s^{-1}
- LHC energy upgrade
  - E_b→13 – 21 TeV (15 → 24 T dipole magnets)

1.4×10^{34}
in 2016

2.06×10^{34}
IN 2017

Beam-Beam Limit Luminosity Equation

injector upgrade

$$L \approx \pi\gamma n_b \frac{(\gamma\varepsilon) f_{rev}}{r_p^2 \beta^*} \Delta Q_{bb}^2 \sqrt{1+\phi^2} F_{profile}$$

LHC + injector changes

IR upgrade

LHC+ injector changes

Summary of Luminosity Upgrade

Scenarios for $L \sim 10^{35} cm^{-2} s^{-1}$ with acceptable heat load and events/crossing

25-ns: push β^* to limit

- Slim magnets inside detector
- Crab Cavities
- High Gradient, Large Aperture Nb_3Sn Quads

50-ns: Fewer bunches, higher charge

- Realizable with $NbTi$
- Beam-Beam tune shift due to large Piwinski angle?
- Luminosity leveling via bunch length and β^* tuning

Indicative Physics Reach

Ellis, Gianotti, ADR
hep-ex/0112004+ updates

Units are TeV (except $W_L W_L$ reach)
$\int$Ldt correspond to <u>1 year of running</u> at nominal luminosity for <u>1 experiment</u>

PROCESS	LHC 14TeV 100 fb^{-1}	SLHC 14TeV 1000 fb^{-1}	SLHC 28TeV 100 fb^{-1}	LinCol 0.8 TeV 500 fb^{-1}	LinCol 5 TeV 100 fb^{-1}
Squarks	2.5	3	4	0.4	2.5
$W_L W_L$	2σ	4σ	4.5σ		
Z'	5	6	8	$8^\dagger$	$8^\dagger$
Extra Dim (δ=2)	9	12	15	5 - $8.5^\dagger$	30 - $55^\dagger$
q^*	6.5	7.5	9.5	0.8	5
Λ_{comp}	30	40	40	100	400
TGC (λ_γ)	0.0014	0.0006	0.0008	0.0004	0.00008

† indirect reach
(from precision measurements)

Approximate mass reach machines:

$\sqrt{s}$ = 14 TeV, L=10^{34} (LHC) : up to ≈ 6.5 TeV
$\sqrt{s}$ = 14 TeV, L=10^{35} (SLHC) : up to ≈ 8 TeV
$\sqrt{s}$ = 28 TeV, L=10^{34} : up to ≈ 10 TeV

OUR PRECISION CHECK OF STANDARD MODEL COUPLINGS WAS DONE AT LEP e^+e^-

NOW THAT WE HAVE OBSERVED THE HIGGS, WE SHOULD DO A PRECISION CHECK OF ITS COUPLINGS AT AN e^+e^- MACHINE.

GIVEN THE ENERGY & LUMINOSITY REQUIRED

CIRCULAR MACHINE IS IMPRACTICAL DUE TO SYNCHROTRON RADIATION

LINEAR COLLIDER → NO SYNCHROTRON RADIATION

LENGTH & COST OF LINEAR COLLIDER DETERMINED BY ACCELERATING VOLTAGE.

Q VALUE & ACCELERATING VOLTAGE

AT RESONANT FREQUENCY OF CAVITIES

$$Q = \frac{\omega_r}{\Delta\omega} = \frac{R_s}{Z}$$

← SHUNT IMPEDENCE

← GEOMETRY FACTOR

ALL RF POWER IS CONVERTED TO HEAT IN R_s

$$P_{RF} = \frac{1}{2} I_0 V_0 = V_0^2/2R_s$$

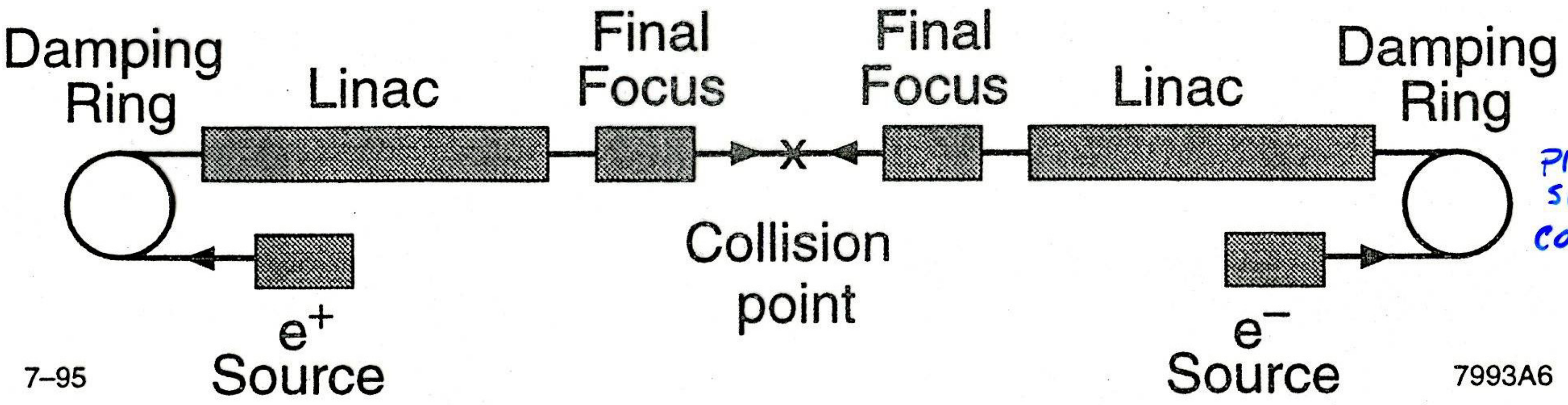
$$V_0 = \sqrt{2 R_s P_{RF}}$$

NEED HIGH RF POWER FOR V_0 HIGH

$$R_s = QZ$$

$$V_0 = \sqrt{2 Z Q P_{RF}}$$

NEED HIGH Q VALUE



PHASE SPACE COOLING

Fig. 4. Schematic layout of a linear collider design.

CAVITY POWER = $V_0^2 / \cancel{\sqrt{}}\, 2R_s = P$

$V_0 = \sqrt{2 R_s P_{RF}}$

EG SLAC

FOR SLAC $V_0\,[\mathrm{MeV}] = 27.5\sqrt{P}\;[\mathrm{MWATT}]$

POWER PRACTICALITIES LIMIT V_0

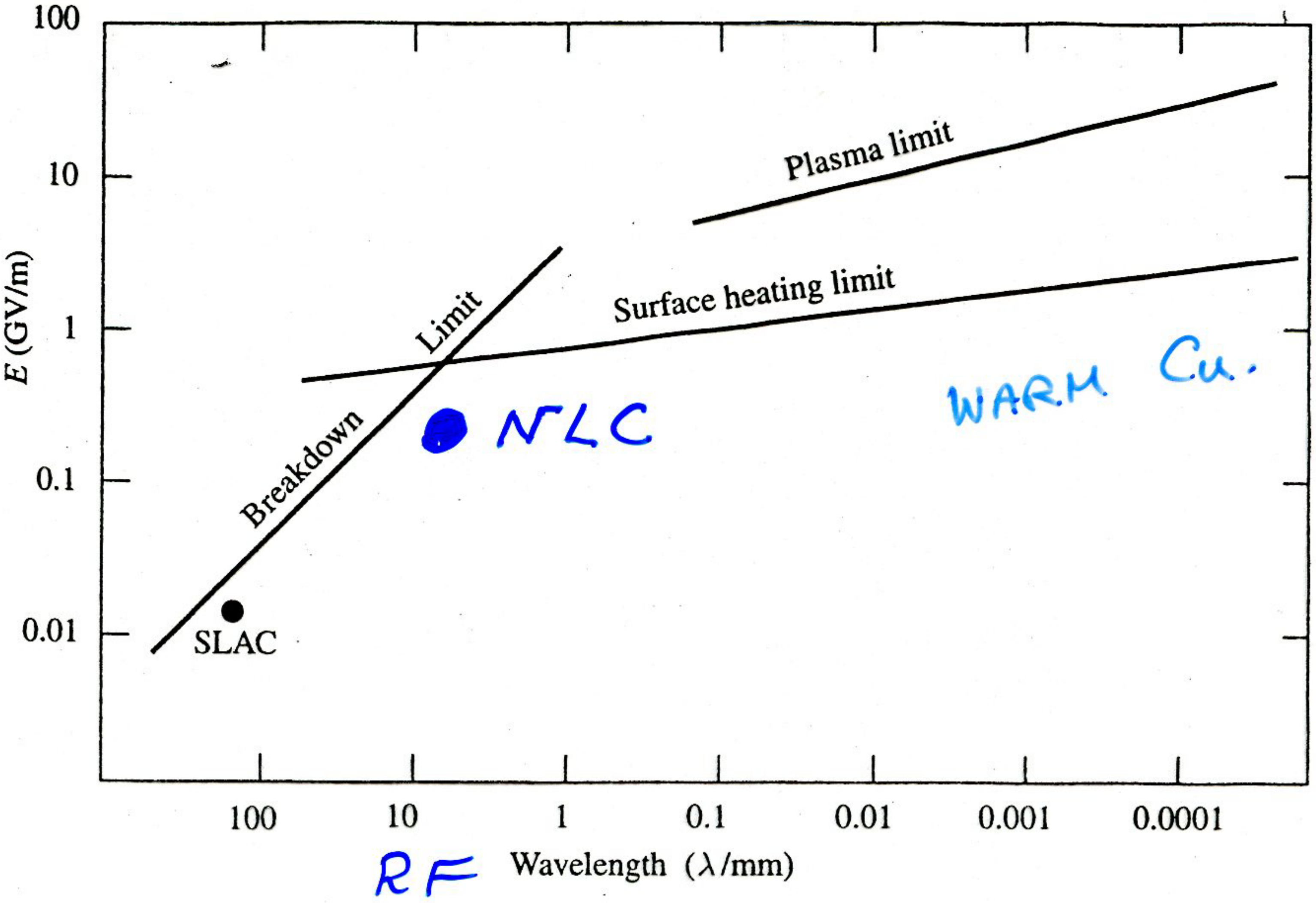


Fig. 11.5 Maximum allowable fields on a copper surface.

PHYSICS $\sigma \sim 1/E_{CM}^2$

MACHINE $\mathcal{L} \sim N^2 f/A$ ← BEAM CROSS SECTION

$P \sim E_{CM} \cdot N \cdot f$

EVENT RATE $= \mathcal{L} \cdot \sigma$ → WANT CONSTANT WITH E_{CM}

WANT $\mathcal{L} \sim E_{CM}^2$

BUT $\mathcal{L} \sim \dfrac{NP}{E_{CM} \cdot A}$ $\left(f \sim \dfrac{P}{E_{CM} N} \right)$

$$E_{CM}^2 \sim \frac{NP}{E_{CM} \cdot A} \qquad A \sim \frac{NP}{E_{CM}^3}$$

$$A \sim \frac{1}{E_{CM}^3}$$ ← TINY BEAM CROSS SECTIONAL AREA

LINEAR COLLIDER – BEAM-BEAM TUNE SHIFT

TINY, INTENSE BEAMS GIVE LARGE $\Delta\nu$

BAD → BEAMSTRALUNG

GOOD → FOCUSING → HIGH $\mathcal{L}$

OF PARTICLES IN OPPOSING BUNCH

$$\Delta\nu = \frac{N_B r_0}{4\pi\gamma\sigma^2} = \frac{N_B r_0}{4\pi\varepsilon_n}$$

NORMALIZED EMITTANCE

BEAM SIZE

$$\mathcal{D} = \frac{\sigma_s}{f} = \frac{N r_0 \sigma_s}{\gamma\sigma^2}$$

DISRUPTION FACTOR

→ RATIO OF BUNCH LENGTH TO FOCAL LENGH

CAN BE >>1 TO GIVE HIGH LUMINOSITY

>1 BEAMS ARE FOCUSED

BEAM - BEAM INTERACTION $\rightarrow \underbrace{f_x \;\; f_z}_{\text{FOCAL LENGTHS}}$

DISRUPTION ANGLE $\theta_0 = \dfrac{\sigma_x}{f_x} = \dfrac{\sigma_z}{f_z} = \dfrac{2 N r_0}{\gamma(\sigma_x + \sigma_z)}$

$$D_{x,z} = \frac{2 N r_0 \sigma_s}{\gamma \sigma_{x,z}(\sigma_x + \sigma_z)} = \frac{\sigma_s}{f_{x,z}} = \frac{\Delta \nu_{x,z}}{A_{x,z}}$$

$$A_{x,z} = \frac{\beta_{x,z}}{\sigma_s}$$

$$\mathcal{L} = \mathcal{L}_0 \times H_D(D_{x,z}, A_{x,z})$$

~ 2 @ SLAC

COLLIDING BUNCHES EMIT SYNCHROTRON RADIATION → BEAMSTRAHLUNG

BEAMSTRAHLUNG PARAMETER $\Upsilon = \frac{2}{3}\frac{\hbar\omega_c}{E} = \frac{\hbar\gamma^2}{mc\rho} = \frac{\gamma B}{B_c}$ ①

B → MAGNETIC FIELD OF COLLIDING BUNCHES

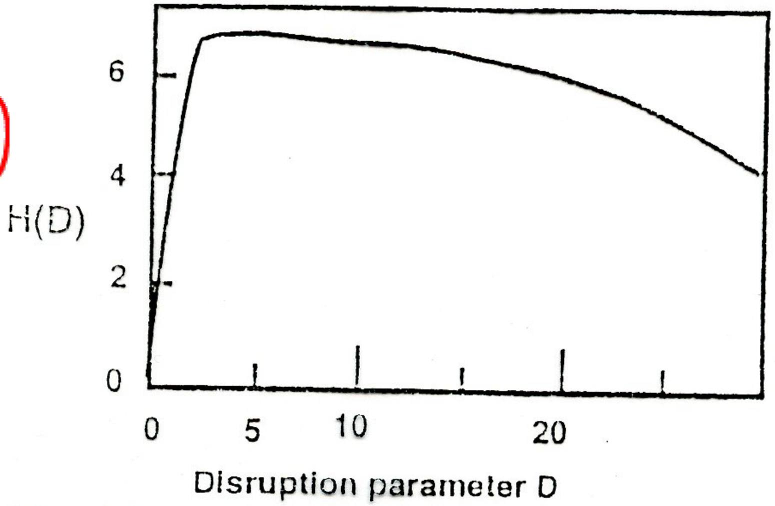
$B_c \rightarrow = m^2c^2/e\hbar \approx 4.4\times10^9\ T$

$\hbar\omega_c \rightarrow \frac{3}{2}\hbar c\gamma^3/\rho$

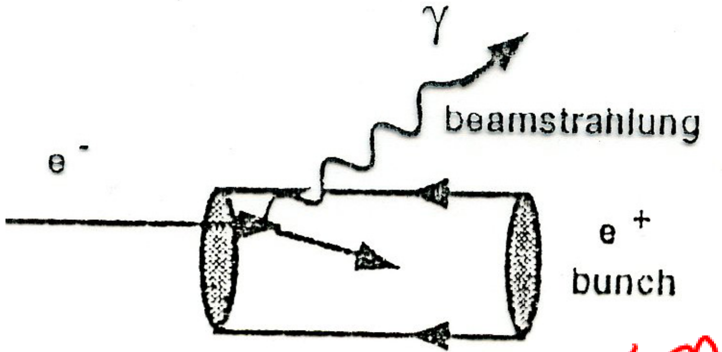
① COMPARES E_{BREMS} to E_{beam}

$$\langle\Upsilon\rangle \approx \frac{5}{12\pi}\frac{N_B r_0 \lambda_c \gamma}{12\pi\sigma_s(\sigma_x+\sigma_z)}$$

$$\mathcal{L} = \mathcal{L}_0 \times H_D(D_{x,z}, A_{x,z})$$



The deflection of the e± due to the other bunch causes radiation known as beamstrahlung.



$$\langle \Upsilon \rangle \approx \frac{5}{12\pi} \frac{N_B r_0 \lambda_c \gamma}{12\pi \sigma_s (\sigma_x + \sigma_z)}$$

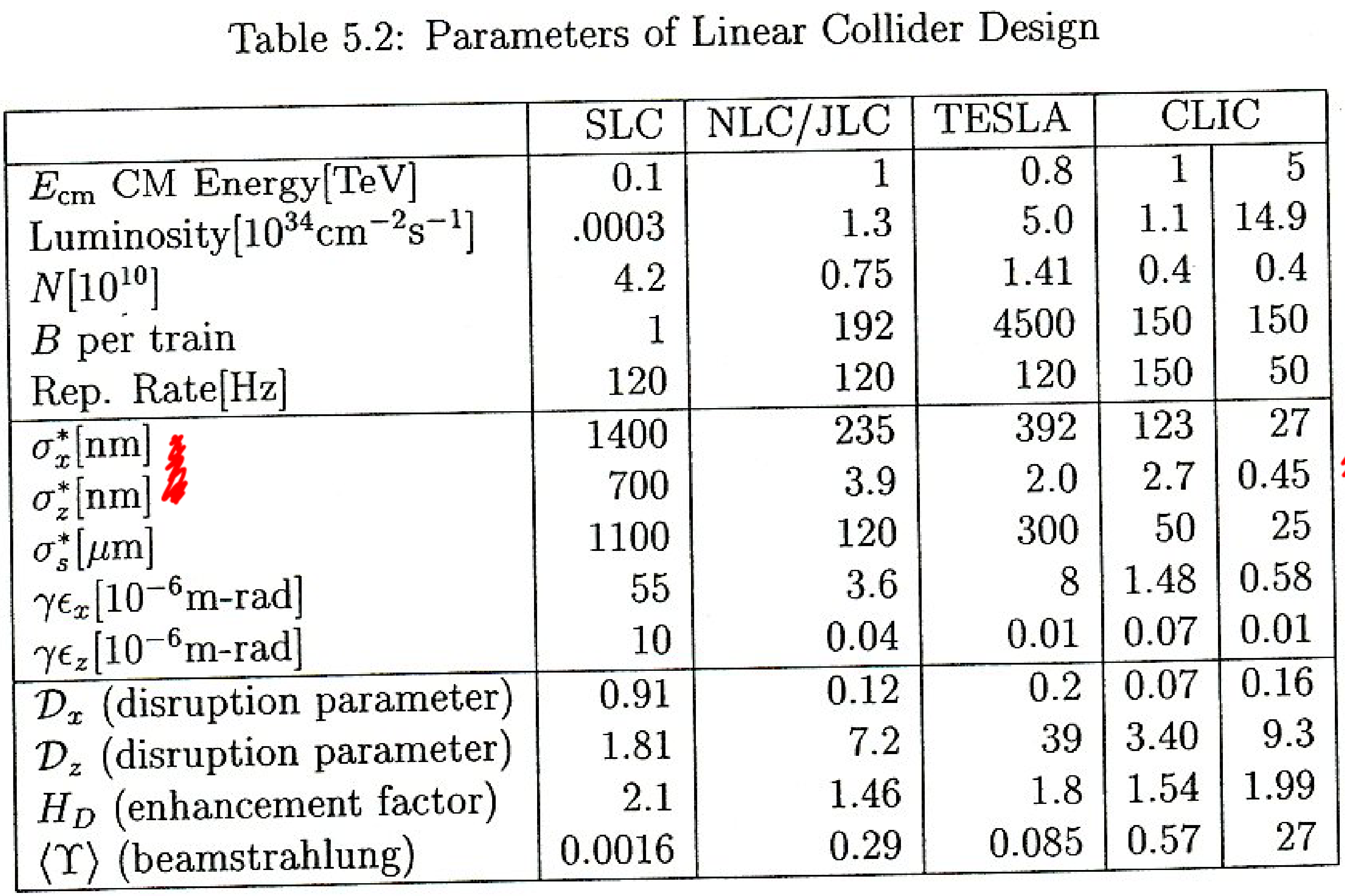
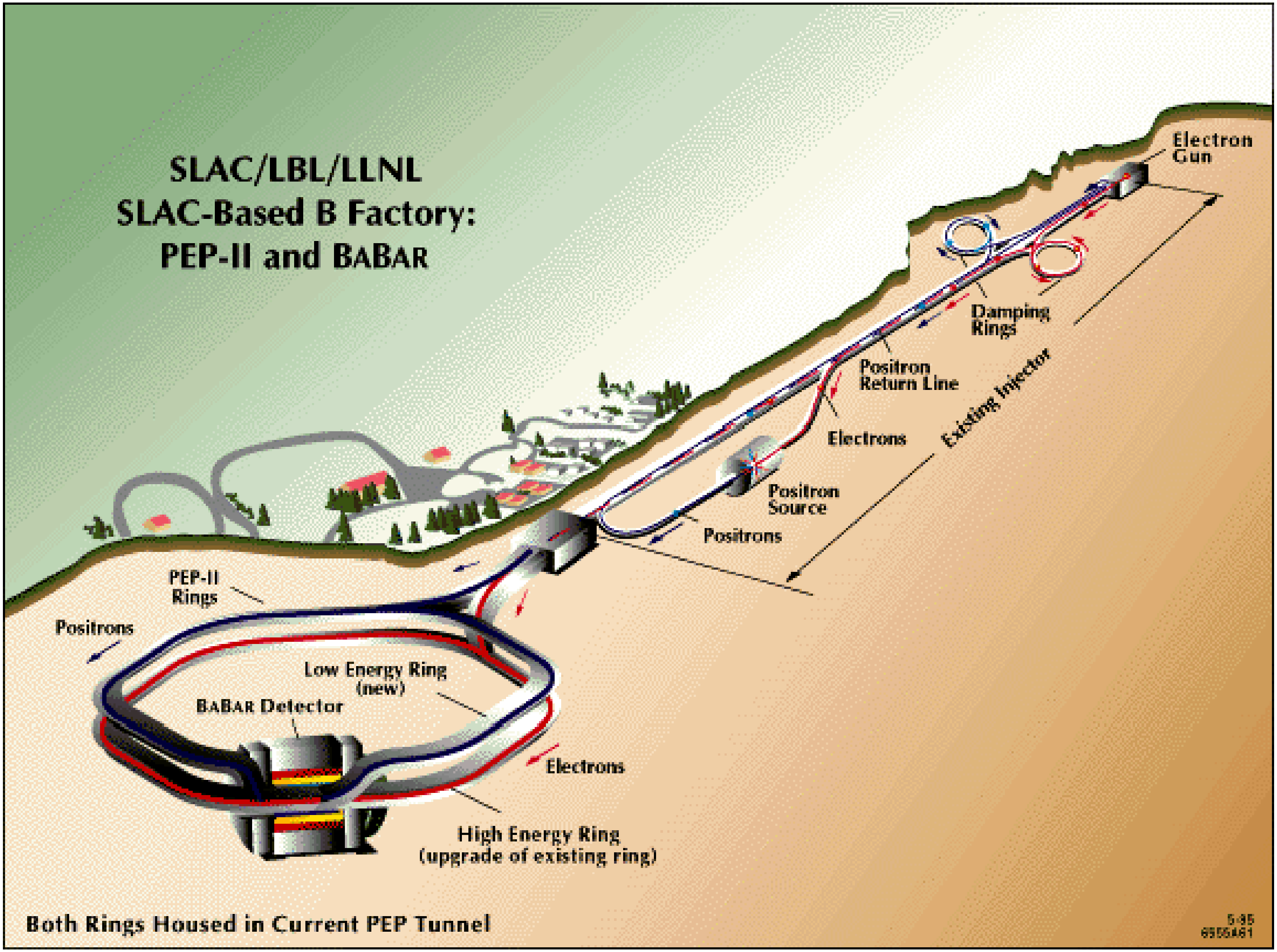


Table 5.2: Parameters of Linear Collider Design

	SLC	NLC/JLC	TESLA	CLIC	
E_{cm} CM Energy[TeV]	0.1	1	0.8	1	5
Luminosity$[10^{34}\text{cm}^{-2}\text{s}^{-1}]$	.0003	1.3	5.0	1.1	14.9
$N[10^{10}]$	4.2	0.75	1.41	0.4	0.4
B per train	1	192	4500	150	150
Rep. Rate[Hz]	120	120	120	150	50
σ_x^*[nm]	1400	235	392	123	27
σ_z^*[nm]	700	3.9	2.0	2.7	0.45
$\sigma_s^*[\mu\text{m}]$	1100	120	300	50	25
$\gamma\epsilon_x[10^{-6}\text{m-rad}]$	55	3.6	8	1.48	0.58
$\gamma\epsilon_z[10^{-6}\text{m-rad}]$	10	0.04	0.01	0.07	0.01
$\mathcal{D}_x$ (disruption parameter)	0.91	0.12	0.2	0.07	0.16
$\mathcal{D}_z$ (disruption parameter)	1.81	7.2	39	3.40	9.3
H_D (enhancement factor)	2.1	1.46	1.8	1.54	1.99
$\langle\Upsilon\rangle$ (beamstrahlung)	0.0016	0.29	0.085	0.57	27

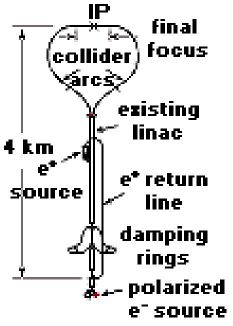
SLAC/LBL/LLNL
SLAC-Based B Factory:
PEP-II and BABAR



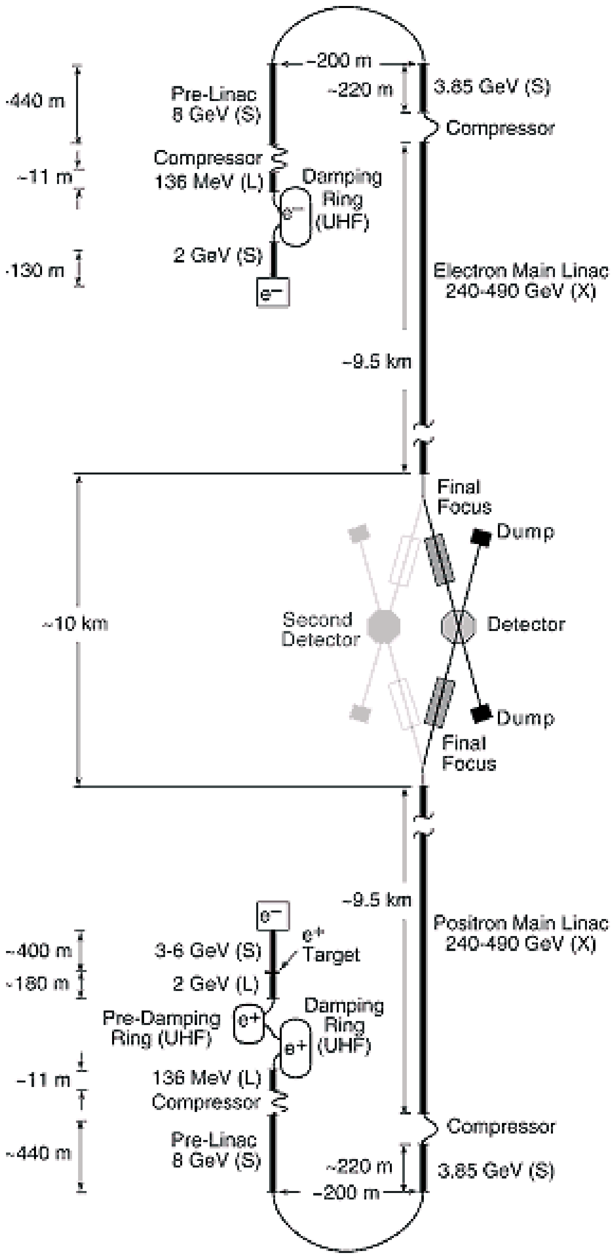
Both Rings Housed in Current PEP Tunnel

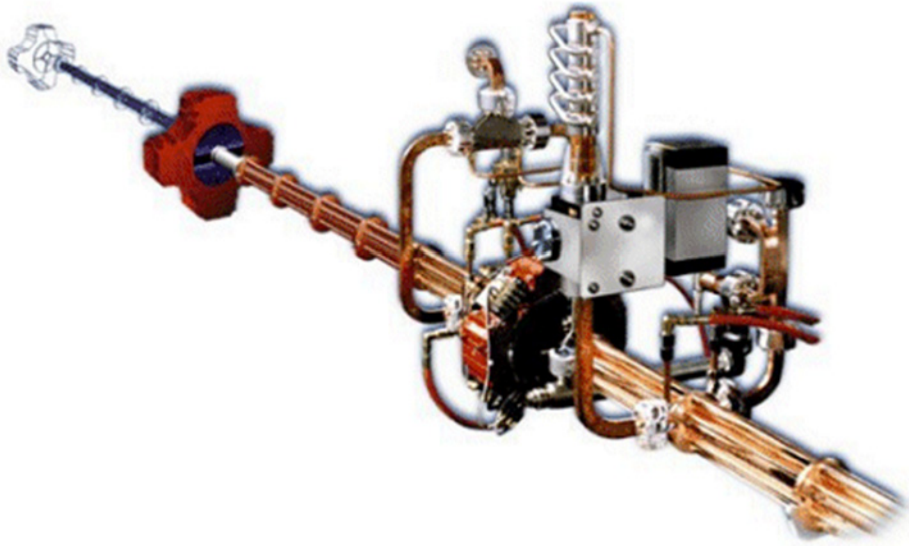
5-95
6555A61

SLC
100 GeV



NLC
0.5 - 1.5 TeV





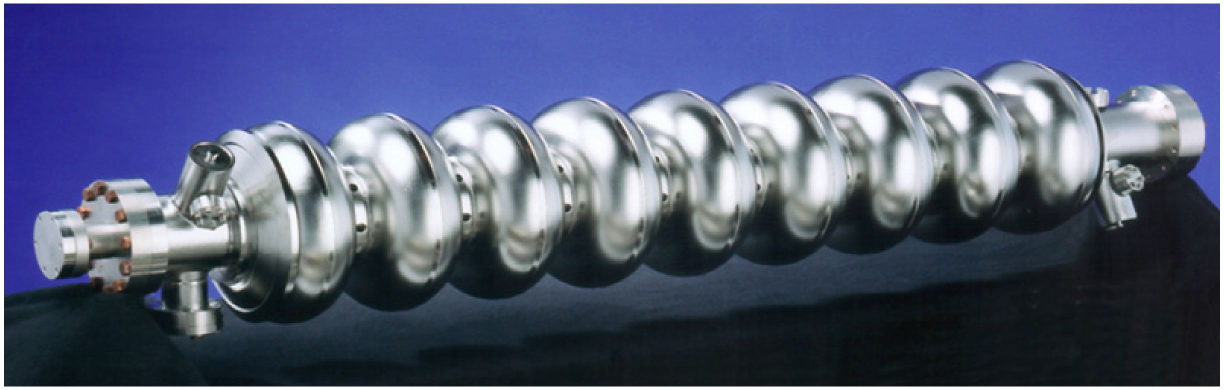
WARM COPPER CAVITY NLC
ABANDONED IN FAVOUR OF MACHINE
USING SUPERCONDUCTING RF ILC

— BREAKDOWN IN Cu CAVITIES
@ HIGH FIELD

— SRF MATURE TECHNOGY
TESLA @ DESY
FLASH @ DESY
XFL @ DESY

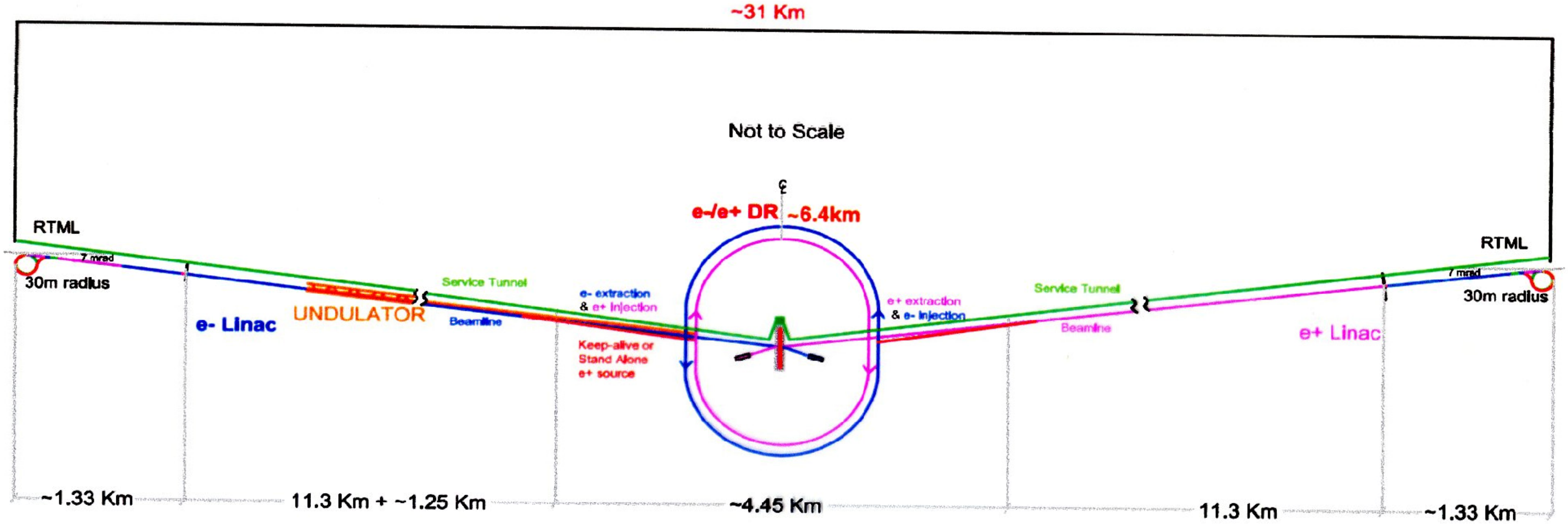
A Primary Cost Driver for ILC -- Superconducting RF Technology

- 1.3 GHz technology developed by TESLA Collaboration,
  R&D from 1992 to reduce the cost per MeV by a factor of 20 from current SCRF installations (CEBAF).
- Increased the operating accelerating gradient by a factor of 5 :
  ~5 MV/m to ~25 MV/m,
  Reduced the cost per meter by a factor of four for large-scale production.
- TESLA cavity R&D based on CERN, CEBAF (JLAB), Cornell University. KEK, Saclay and Wuppertal.
- Basic element of the technology is a nine-cell 1.3 GHz niobium cavity.
- Approximately 160 of these cavities have been fabricated by industry as part of R&D program at DESY. → NOW XFEL @ DESY



INTERNATIONAL LINEAR COLLIDER

- ECM = 500GeV max within a site footprint of ~31km.
- Main Linacs: superconducting cavities
- Eacc = 31.5MV/m (16000 x 9-cell cavities → 2 x ~12km)
- Injectors: Polarized (P~80%) e- source
- 2 damping rings (e- and e+) around interaction region.



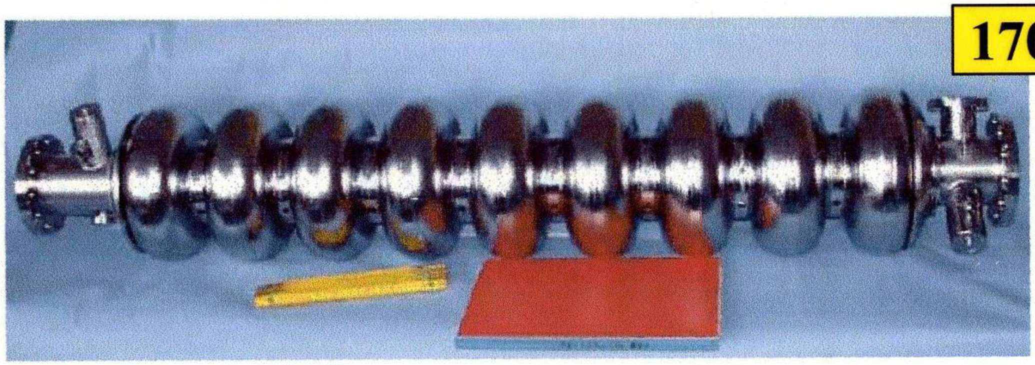
Schematic Layout of the 500 GeV Machine

The base technology

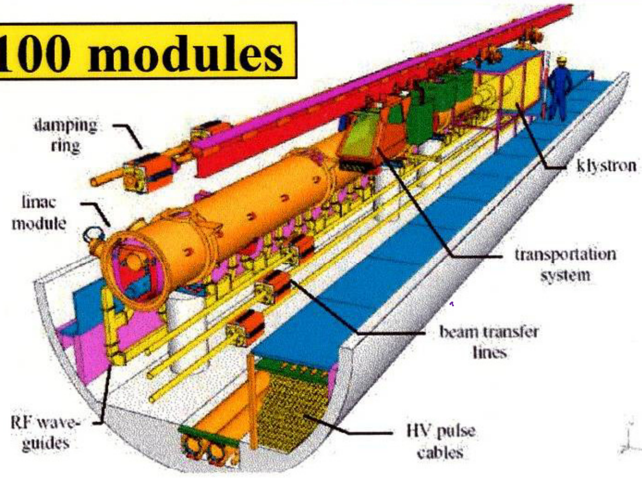
The core technology for the ILC is 1.3GHz superconducting RF cavity intensely developed in the TESLA collaboration, which was recommended for the ILC by the ITRP on 2004 August.
The cavities are installed in a long cryostat and cooled at 2k, and operated at gradient 31.5MV/m.

17000 cavities

~ 31 km LON



2100 modules



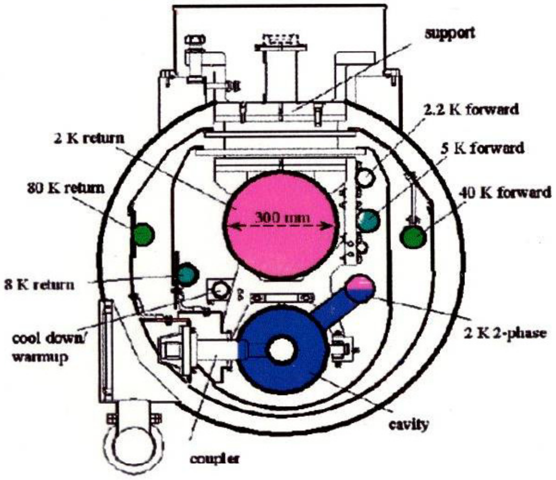
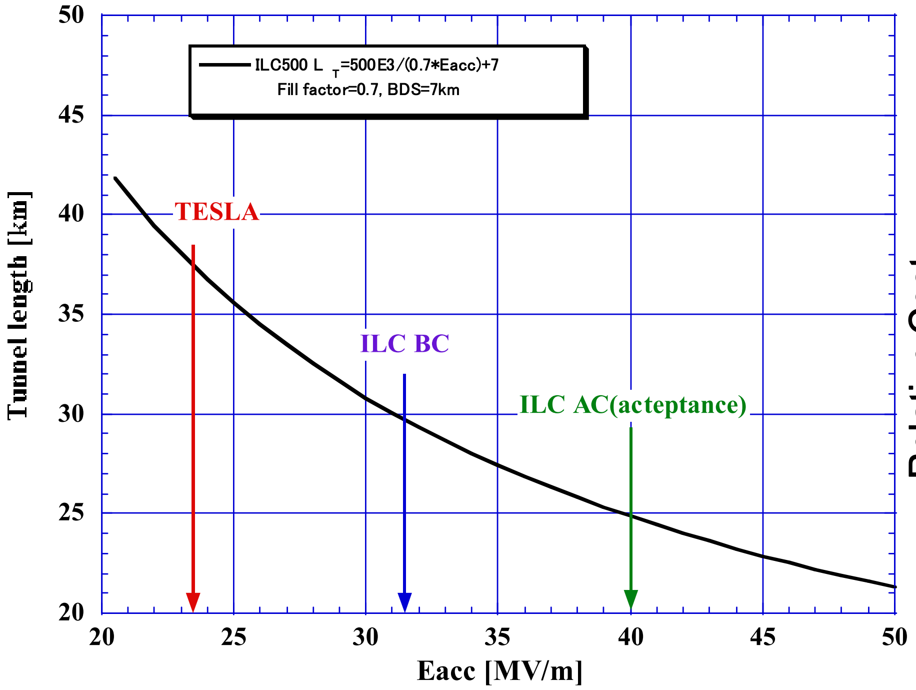
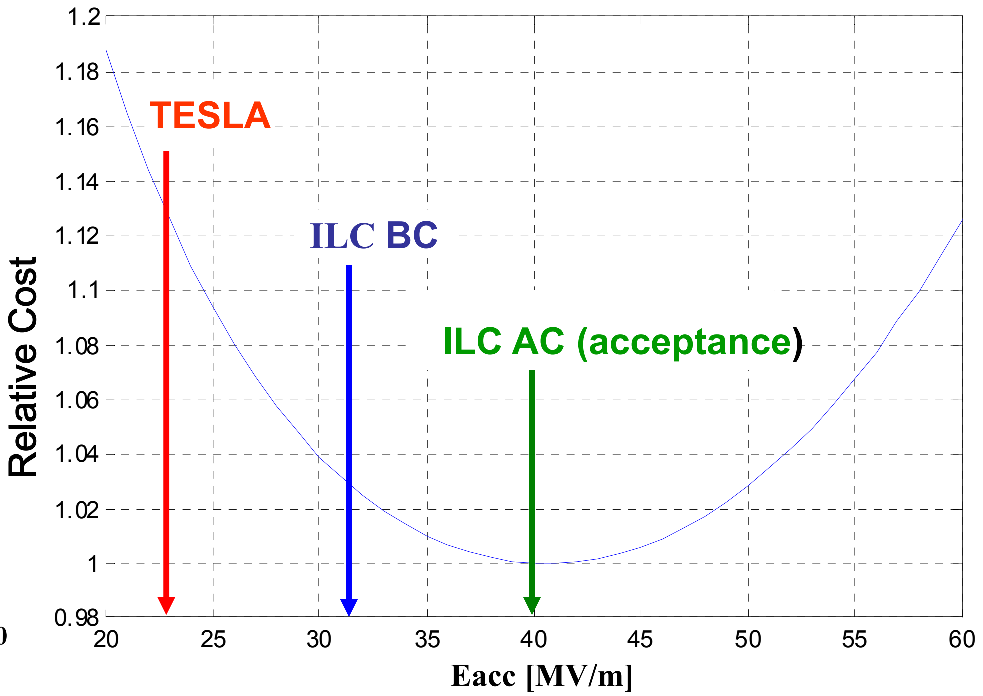


Figure 3.3.2: *Cross section of cryomodule.*

Why Aim for Higher Gradient ?





ILC500 Gradient dependence with tunnel length and cost

$$\text{Total cost} = \text{Tunnel}(1/\text{Eacc}) + \text{Cryomodul}(1/\text{Eacc}) + \text{RF}(\text{Eacc}) + \text{Cryoplant}(\text{Eacc}^2) + \text{Cryo-Operation}(\text{Eacc}^2) + \text{Beampower}(\text{const})$$

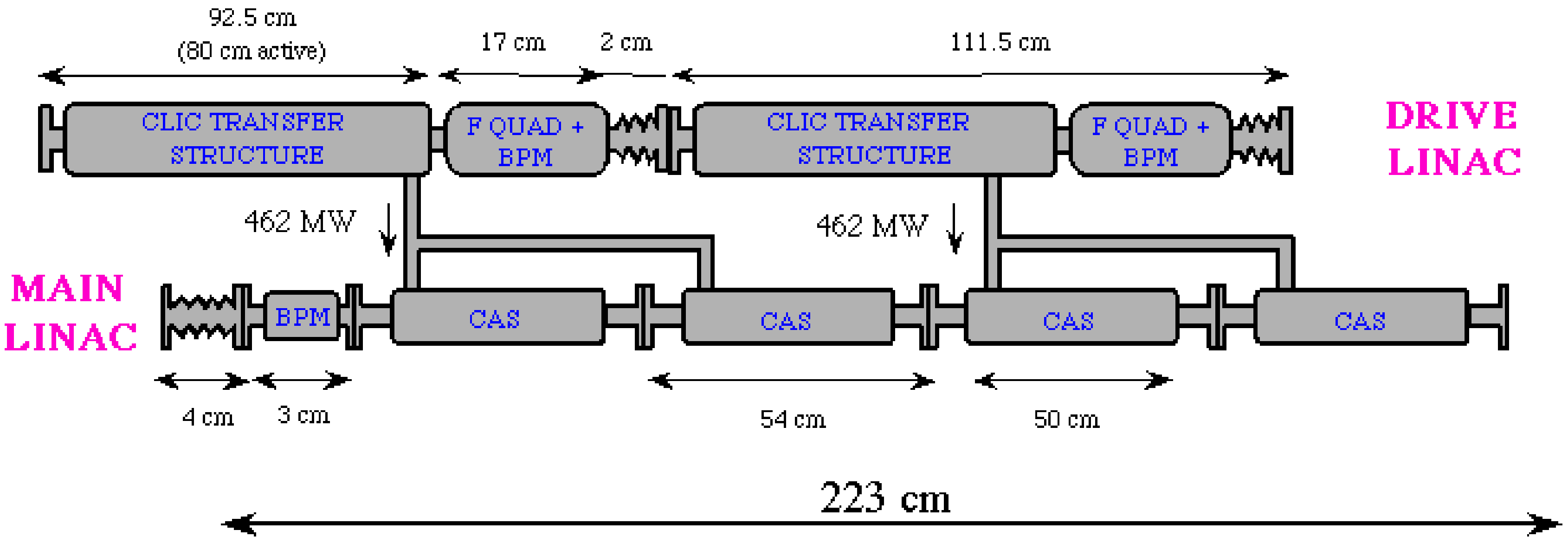
$$= [C_T + C_{CM}] \cdot \frac{1}{\text{Eacc}} + C_{RF} \cdot \text{Eacc} + [C_{\text{Cryplant}} + C_{\text{Cryoop}}] \cdot \text{Eacc}^2 + C_{\text{Beampower}}$$

ILC Main LINAC Cavity Baseline

ILC parameters related to SCRF		BCD: Baseline	ACD: Alternative
Cavity Shape		TESLA	Low loss Reentrant
Acceptance Performance	Gradient [MV/m]	35	40
	Qo	0.80E10	0.80E10
Operation Performance	Gradient [MV/m]	31.5	36
	Qo	1.0E10	1.0E10

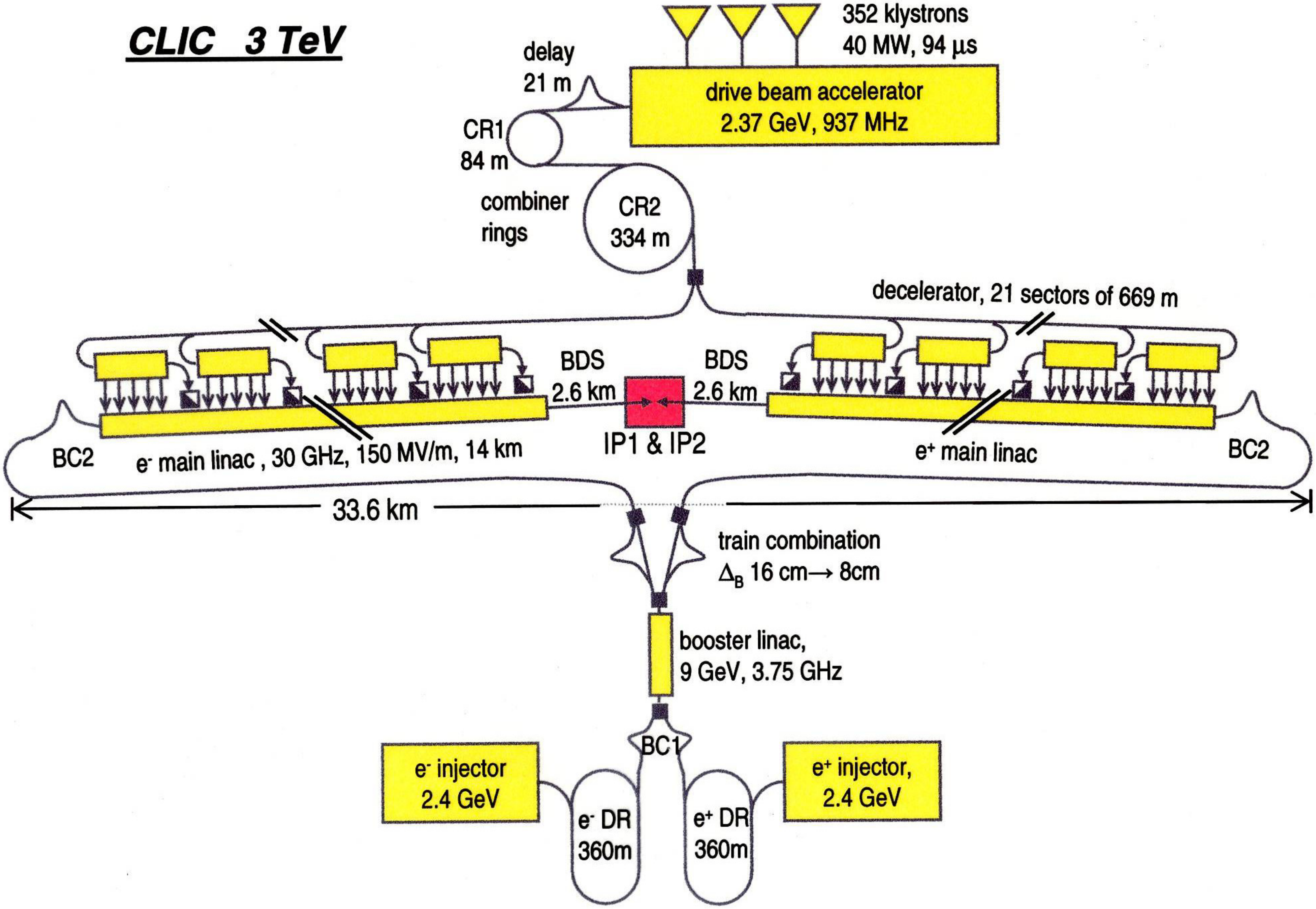
TWO BEAM ACCELERATION (TBA)

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



CLIC module layout
3 TeV

CLIC 3 TeV


352 klystrons
40 MW, 94 µs
delay
21 m
drive beam accelerator
2.37 GeV, 937 MHz
CR1
84 m
combiner
rings
CR2
334 m
decelerator, 21 sectors of 669 m
BDS
2.6 km
BDS
2.6 km
IP1 & IP2
BC2
e⁻ main linac , 30 GHz, 150 MV/m, 14 km
e⁺ main linac
BC2
33.6 km
train combination
Δ_B 16 cm→ 8cm
booster linac,
9 GeV, 3.75 GHz
BC1
e⁻ injector
2.4 GeV
e⁻ DR
360m
e⁺ DR
360m
e⁺ injector,
2.4 GeV

Limitations of E_{ACC}

Field emission due to surface electric field

Consequences:

- Local plasma triggered by field emission ⇔ RF break down ⇔ Erosion of surface
- Break down rate ⇒ Operation efficiency
- Dark current capture
  ⇒ Efficiency reduction+activation+detector backgrounds+wakefields

Surface magnetic field

Pulsed heating ⇒ material fatigue ⇒ cracks

Dark energy

RF power flow and/or iris aperture apparently have a strong impact on achievable E_{acc} and on surface erosion. Mechanism not fully understood.

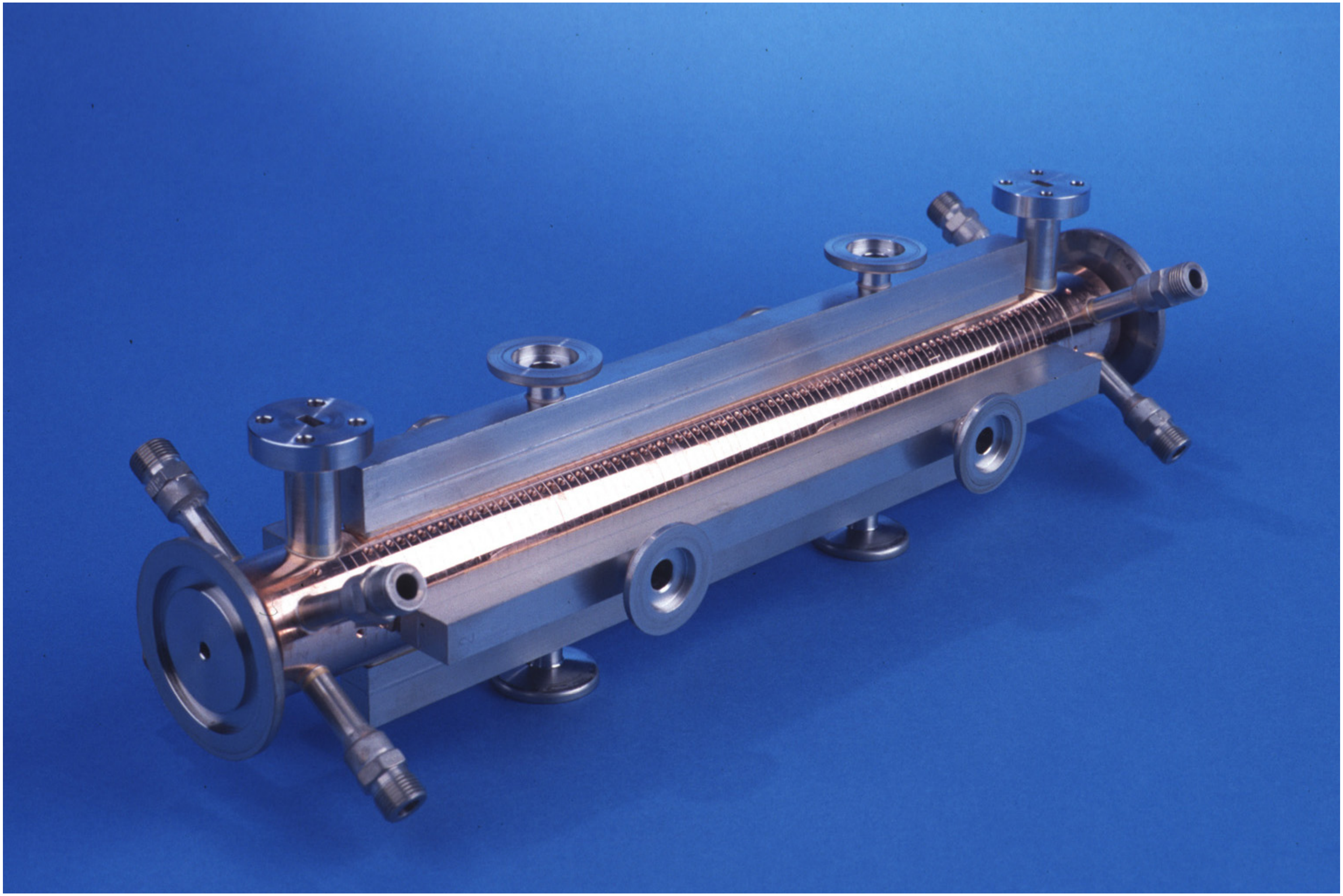
Gradient Limits

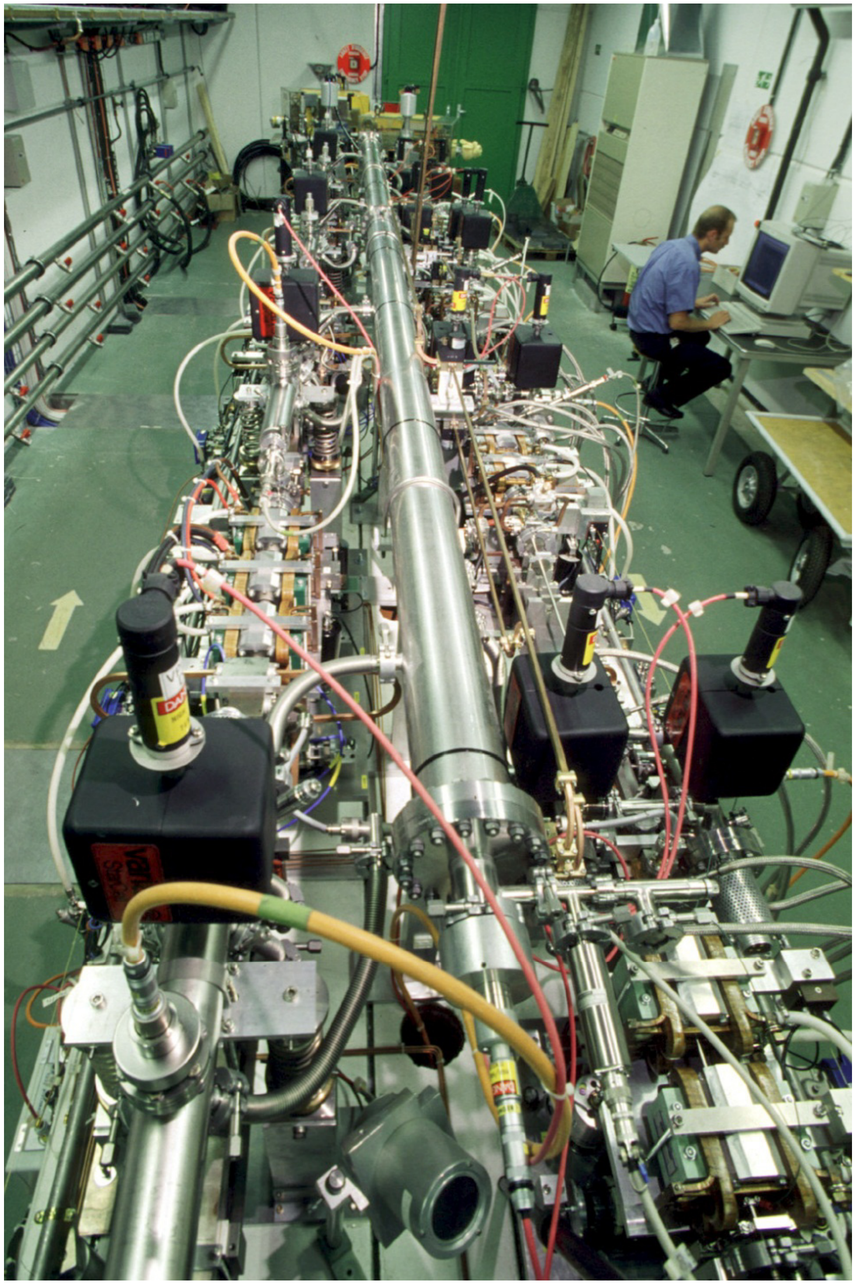
SC cavities ≈ 50 MV/m
90% of theoretical field limit given by critical B field

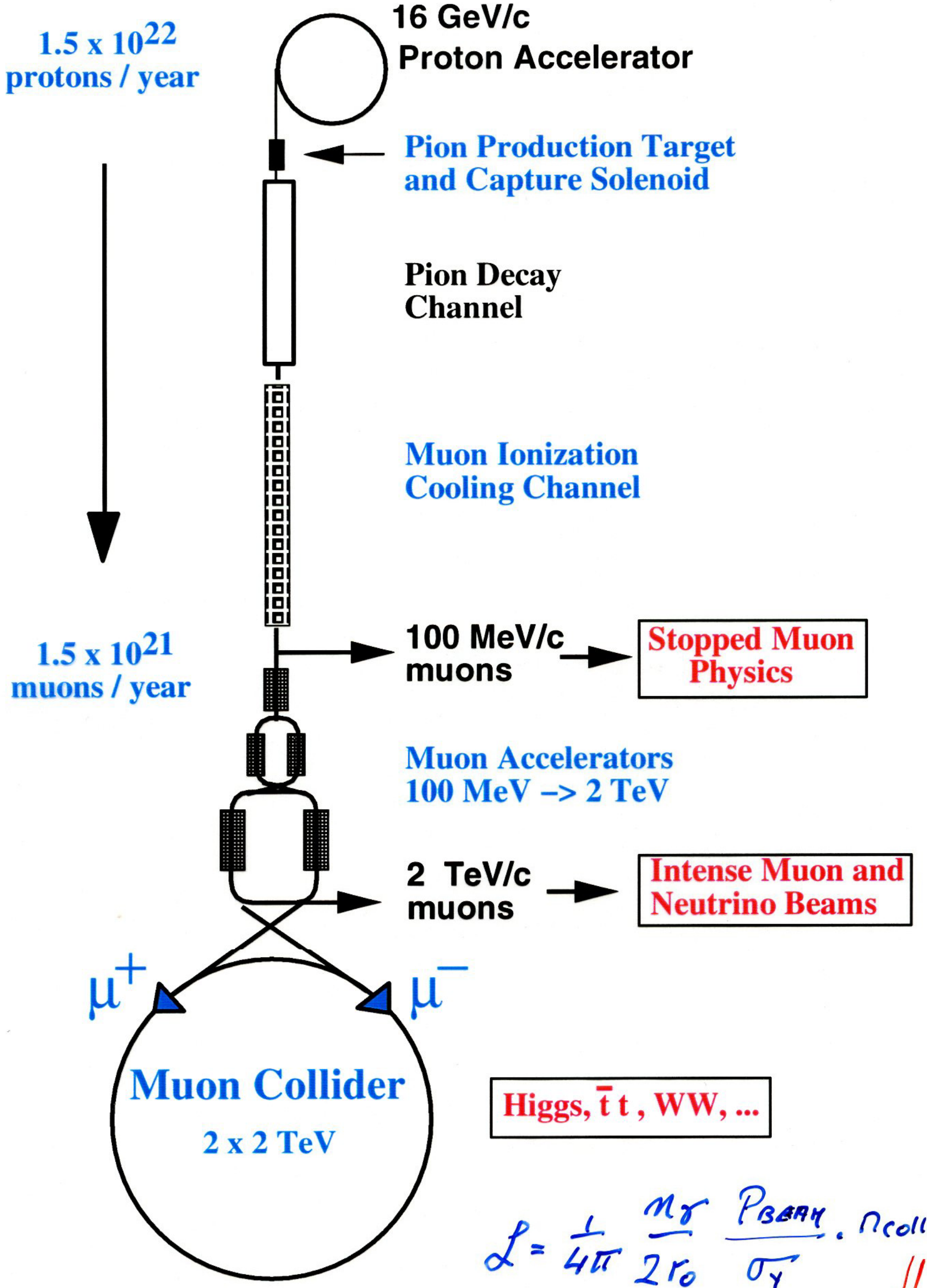
NC cavities ≈200 MV/m
5% of theoretical field limit given by Fowler-Nordheim law

Theoretical understanding of NC breakdown insufficient for safe design guidelines !

⇒ Design of high field NC structures has to rely on extrapolation of existing data plus extensive prototype power testing !







1.5 x 10^{22} protons / year

16 GeV/c Proton Accelerator

Pion Production Target and Capture Solenoid

Pion Decay Channel

Muon Ionization Cooling Channel

1.5 x 10^{21} muons / year

100 MeV/c muons

Stopped Muon Physics

Muon Accelerators 100 MeV –> 2 TeV

2 TeV/c muons

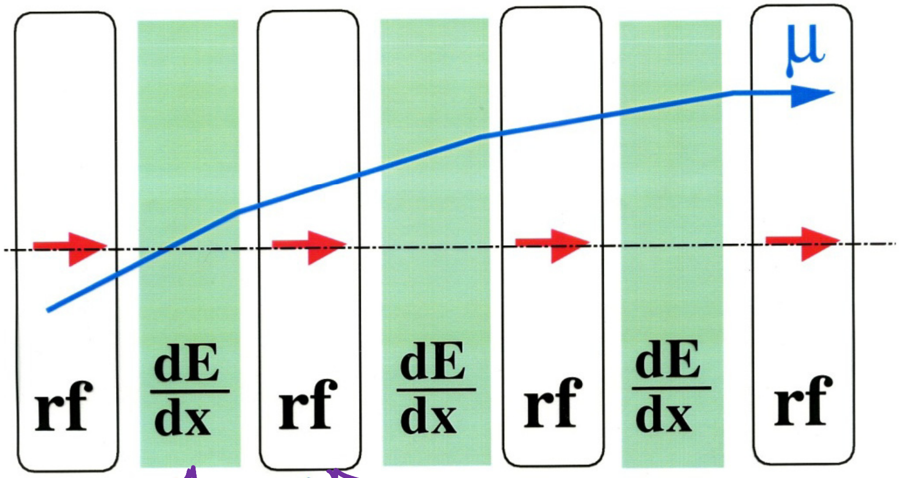
Intense Muon and Neutrino Beams

Muon Collider

2 x 2 TeV

Higgs, $\bar{t}$ t , WW, ...

Ionization Cooling



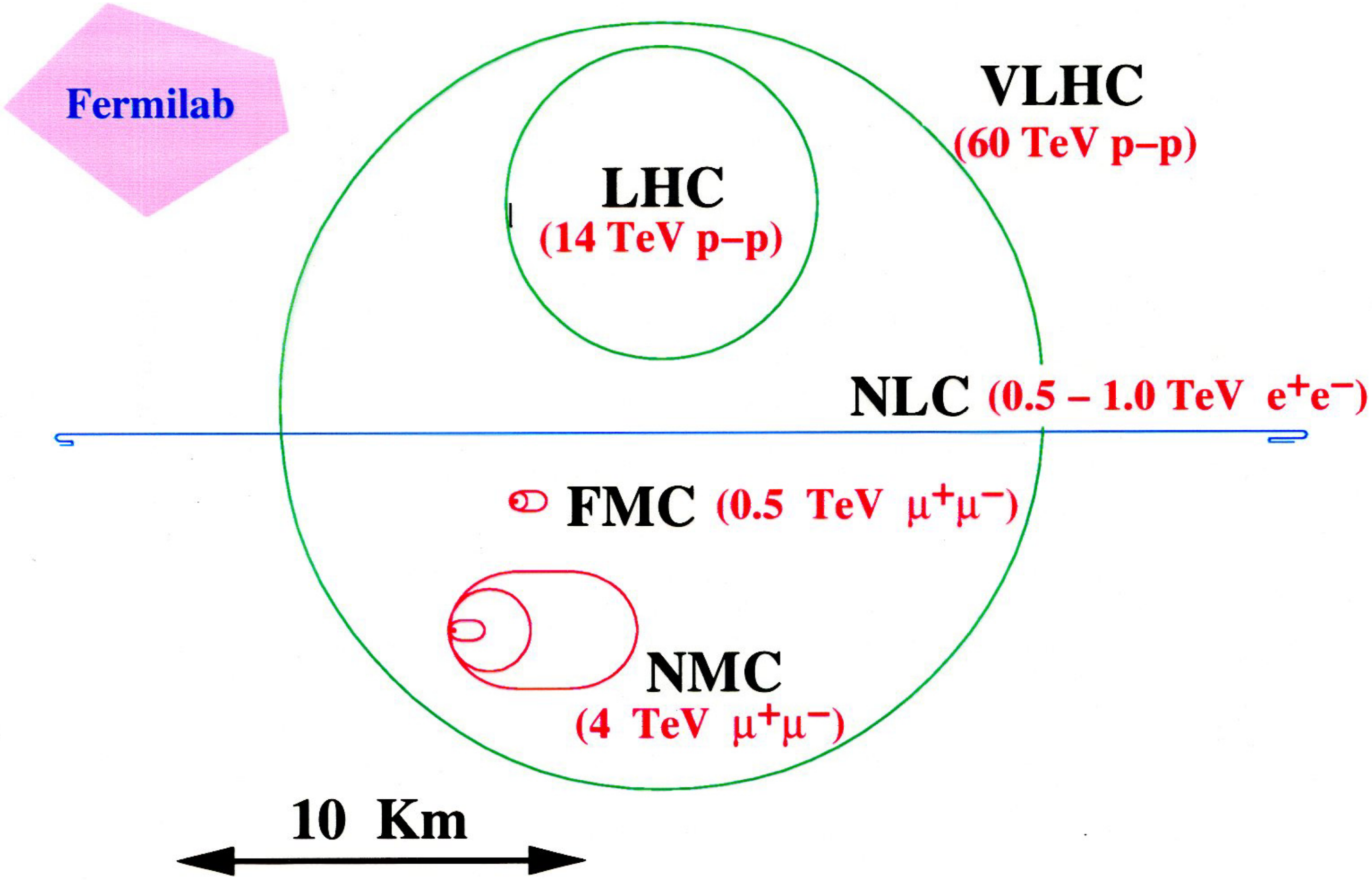
LOSE $P_\perp, P_L$

RESTORE P_L

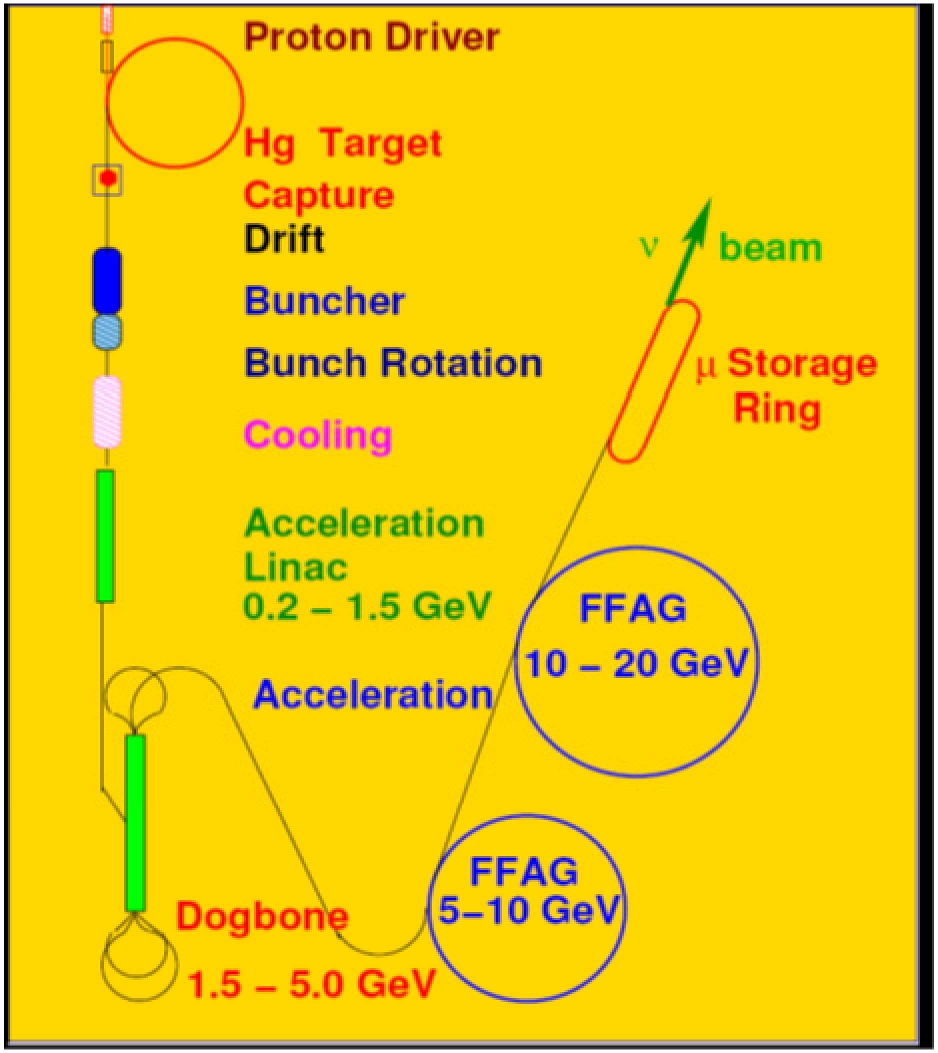
$$\mathcal{L} = \frac{1}{4\pi} \frac{n_\gamma}{2 r_0} \frac{P_{BEAM}}{\sigma_y} \cdot n_{collisions}$$

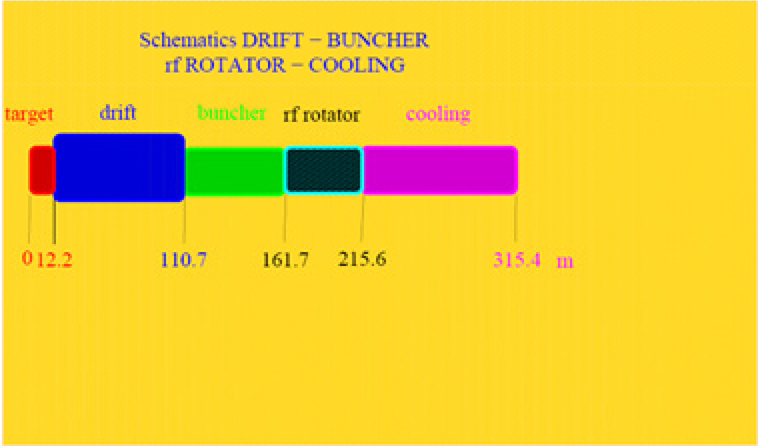
|| #1

$$r_0^{\mu} = \frac{r_0^{e}}{200}$$


Fermilab
VLHC
(60 TeV p–p)
LHC
(14 TeV p–p)
NLC (0.5 – 1.0 TeV e^+e^-)
FMC (0.5 TeV $\mu^+\mu^-$)
NMC
(4 TeV $\mu^+\mu^-$)
10 Km

Schematics of a Neutrino Factory (US Study IIa)

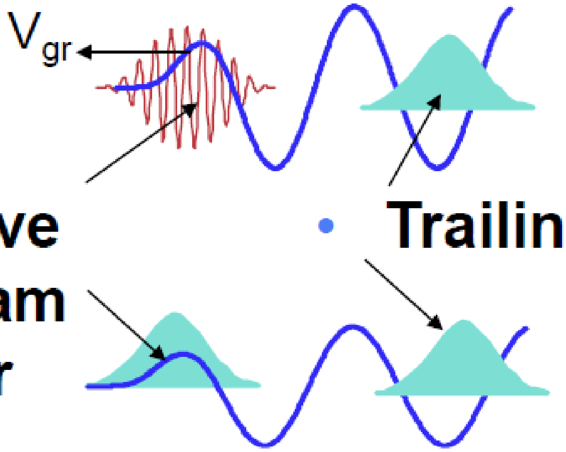




Plasma Based Accelerators

- **Laser Wake Field Accelerator**

  A single short-pulse of photons



- **Drive beam**
- **Trailing beam**

- **Plasma Wake Field Accelerator**

  A high energy electron bunch

- **Wake: phase velocity = driver velocity**

Linear Plasma Wakefield Theory

$$(\partial_t^2 + \omega_p^2)\frac{n_1}{n_o} = -\omega_p^2\left(\frac{n_b}{n_o} + k_p^2\nabla^2\sqrt{1+\langle a_o^2\rangle}\right)$$

Large wake if laser amplitude **$a_o=eE_o/m\omega_o c \sim 1$** or a beam density **$n_b \sim n_o$**

And τ_{pulse} of order $\pi\omega_p^{-1} \sim 100\mathrm{fs}\,(10^{17}/n_o)^{1/2}$ and spot size c/ω_p:

$\Rightarrow P \sim 15\ \mathrm{TW}\,(\tau_{pulse}/100\mathrm{fs})^2$ laser

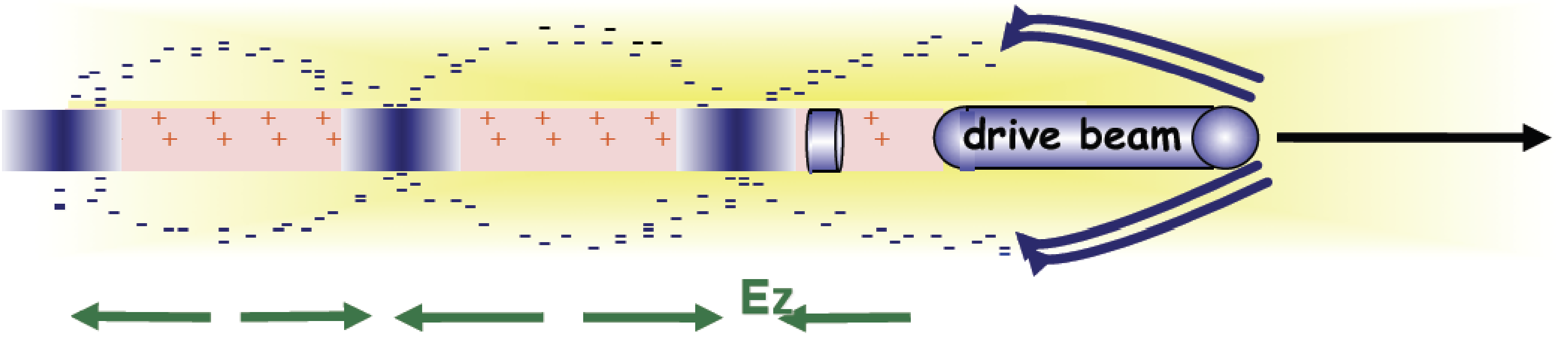
$\Rightarrow Q/\tau_{pulse} = 1\mathrm{nCoul}/100\mathrm{fs}$ (~10 kA) beam

$$\nabla \bullet E = -4\pi e n_1 \Rightarrow \quad eE = \frac{n_1}{n_o}\sqrt{\frac{n_o}{10^{16}cm^{-3}}}\,10\,GeV/m\,\cos\omega_p(t - z/c)$$

Plasma Wakefield Accelerators

(Blowout Regime)

Rosenzweig et al. 1990

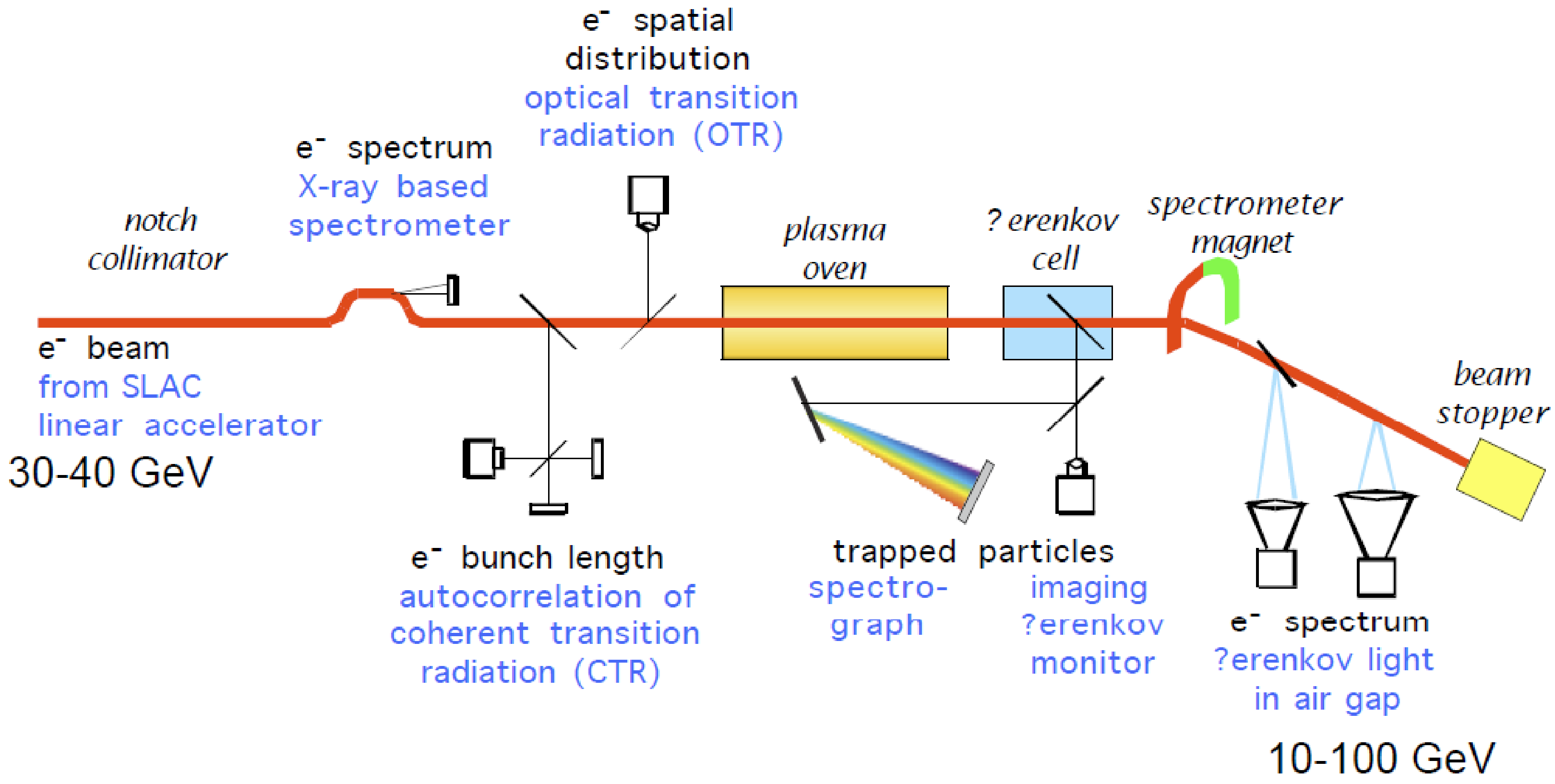


- **Plasma ion channel** exerts restoring force => space charge oscillations

  Linear focusing force on beams (F/r=2πne^2/m)
  - Synchrotron radiation
  - Scattering

- **Nonlinear Theory** : *W. Lu et al., PRL 16, 16500 [2006]*

Plasma Wakefield Acceleration Experiments @ SLAC



notch collimator

e^- beam
from SLAC
linear accelerator
30-40 GeV

e^- spectrum
X-ray based
spectrometer

e^- spatial
distribution
optical transition
radiation (OTR)

e^- bunch length
autocorrelation of
coherent transition
radiation (CTR)

plasma oven

? erenkov cell

spectrometer magnet

trapped particles

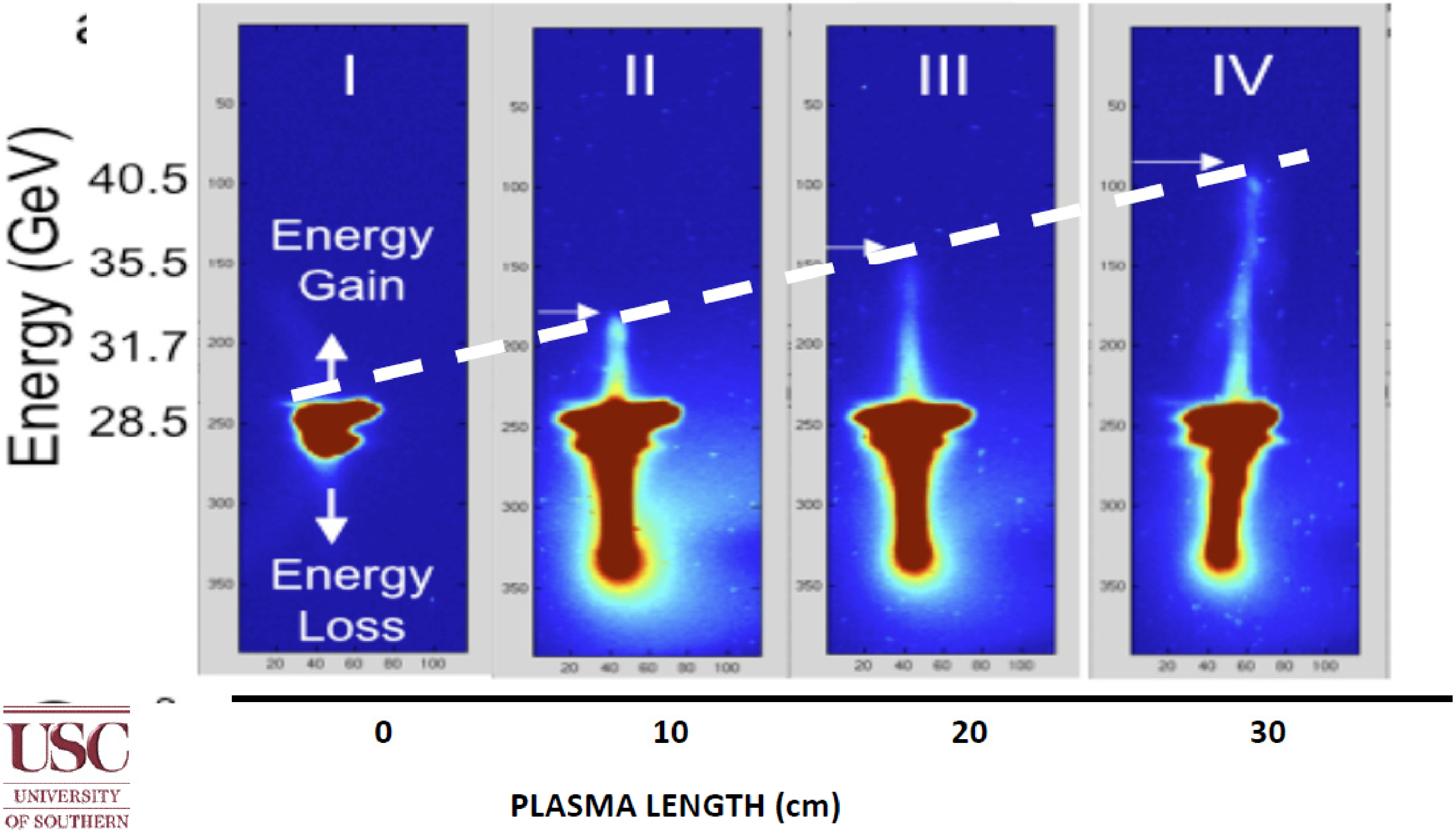
spectro-
graph

imaging
?erenkov
monitor

e^- spectrum
?erenkov light
in air gap
10-100 GeV

beam stopper

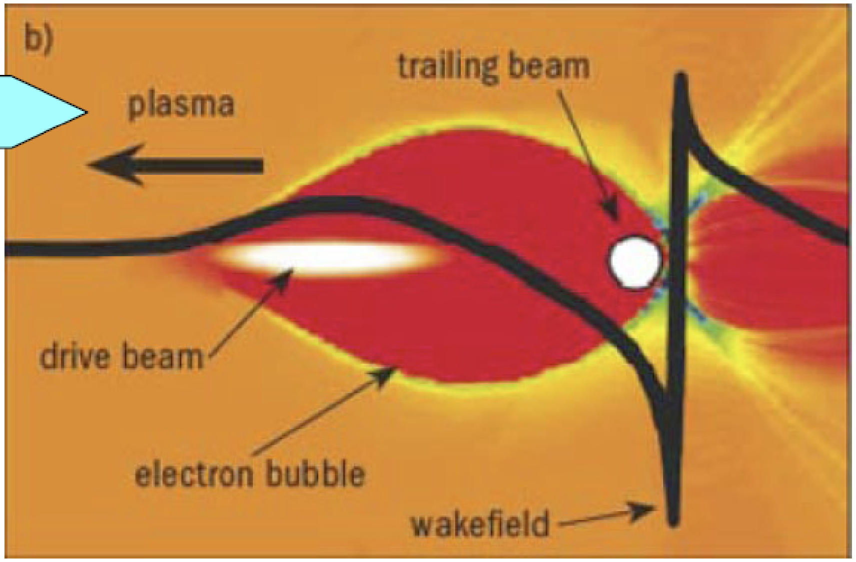
Energy Gain Scales Linearly with Length

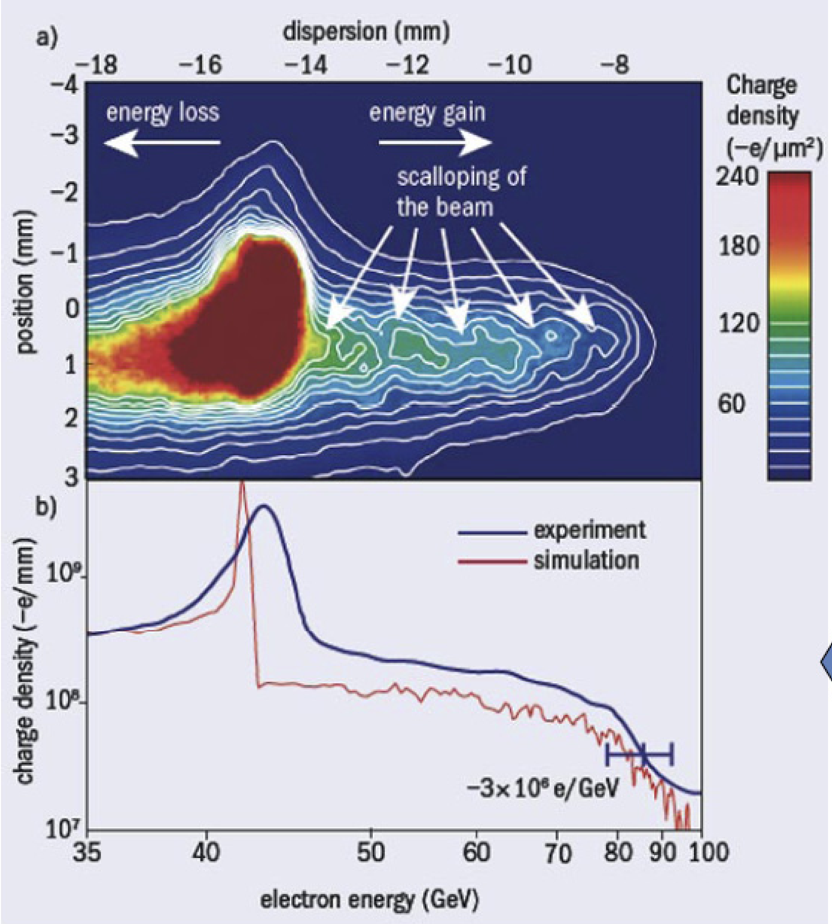


42GeV e-beam energy doubled by PLASMA WAKEFIELD ACCELERATOR

I. Blumenfeld et al., Nature 455, 741, 2007

Plasma wakefield in the “bubble” regime





Energy spectrum of E167 SLAC Plasma Accelerator Experiment for the 42 GeV electron beam after passing through a 85 cm long plasma of density 2.7×10^{17} cm^{-3}

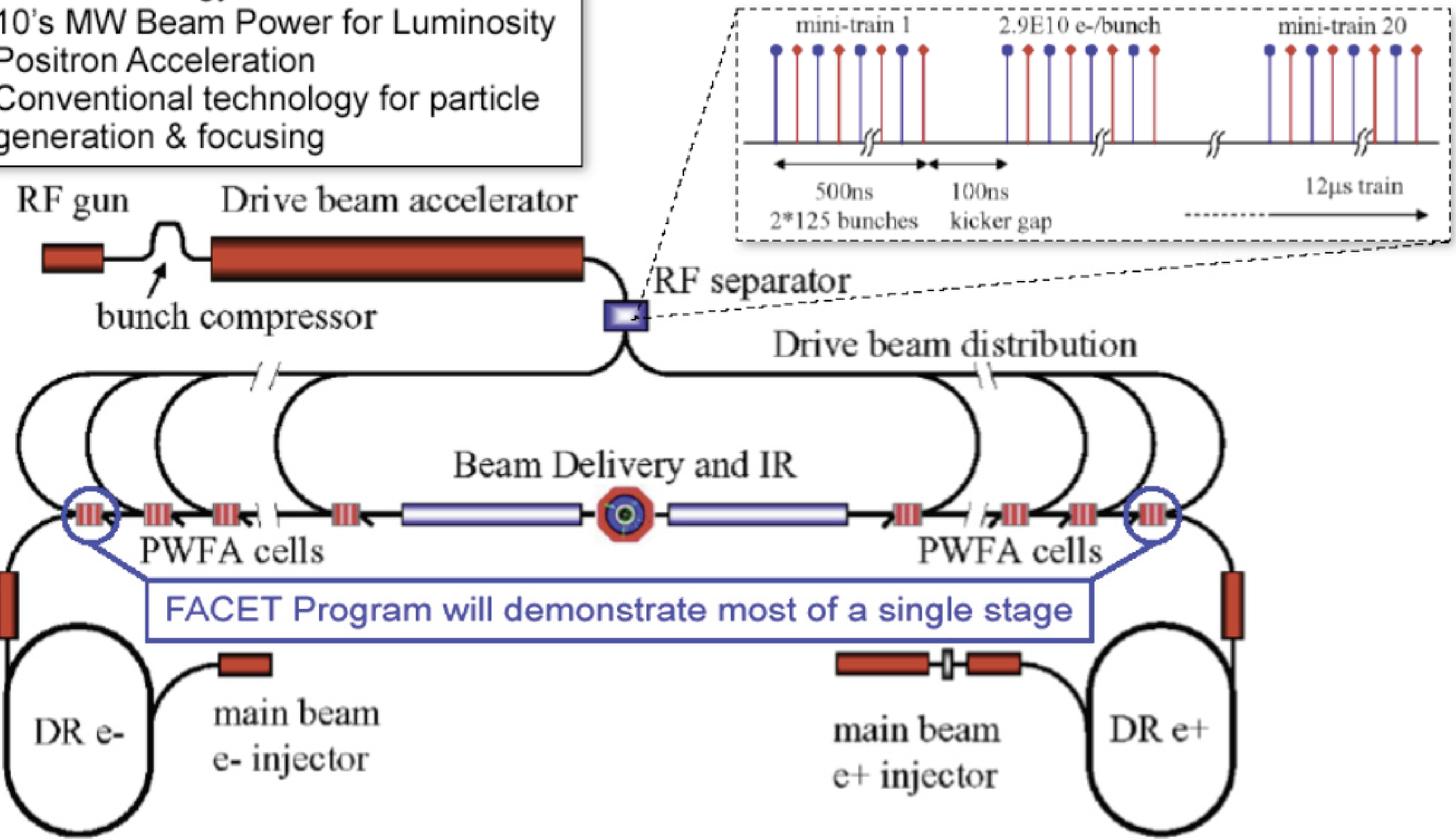
From Science to a Collider

Requirements for High Energy Physics

- High Energy
- High Luminosity (event rate)
  - $L=f_{rep}N^2/4\pi\sigma_x\sigma_y$
- High Beam Power
  - ~20 MW
- High Beam Quality
  - Energy spread $\delta\gamma/\gamma \sim .1 - 10\%$
  - Low emittance: $\varepsilon_n \sim \gamma\sigma_y\theta_y << 1$ mm-mrad
- Reasonable Cost : less than $5 B for 1 TeV CM
  - Gradients > 100 MeV/m
  - Efficiency > few %

A Concept for a Plasma Wakefield Accelerator Based Linear Collider

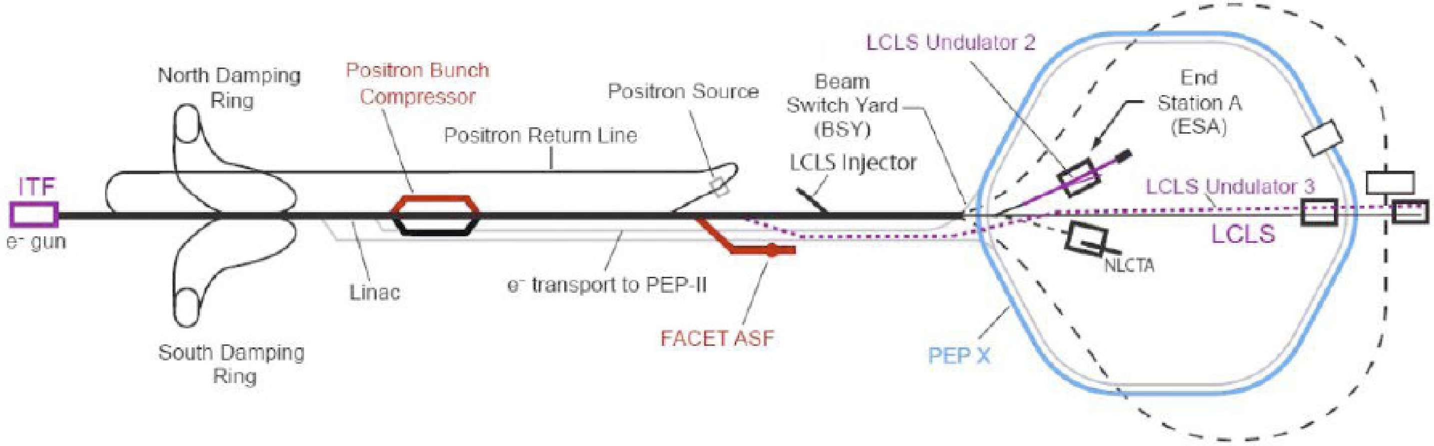
- TeV CM Energy
- 10's MW Beam Power for Luminosity
- Positron Acceleration
- Conventional technology for particle generation & focusing



FACET Program will demonstrate most of a single stage

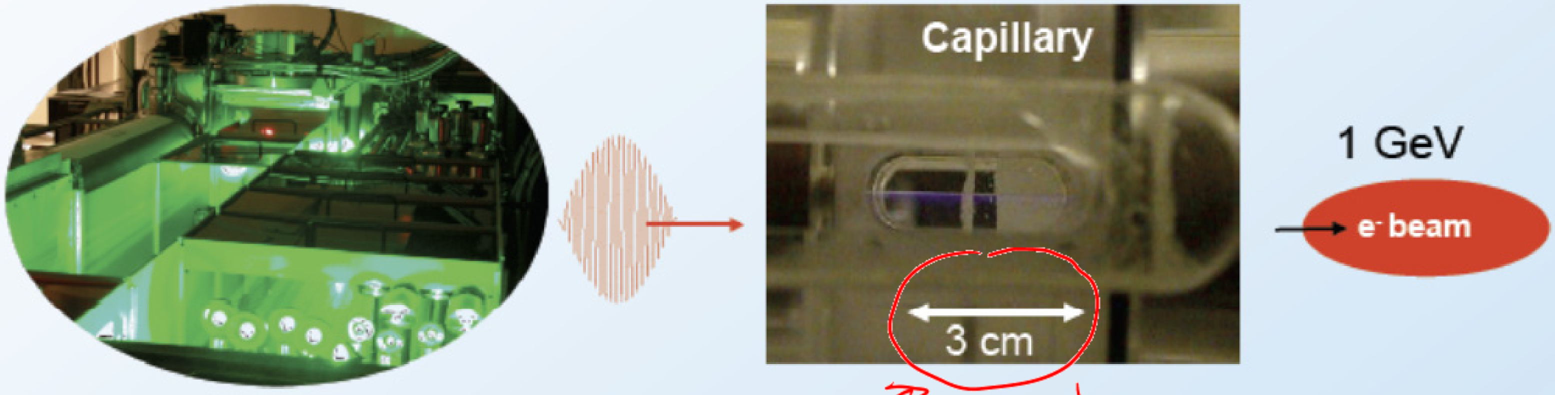
FACET: Facility for Advanced Accelerator Experimental Tests

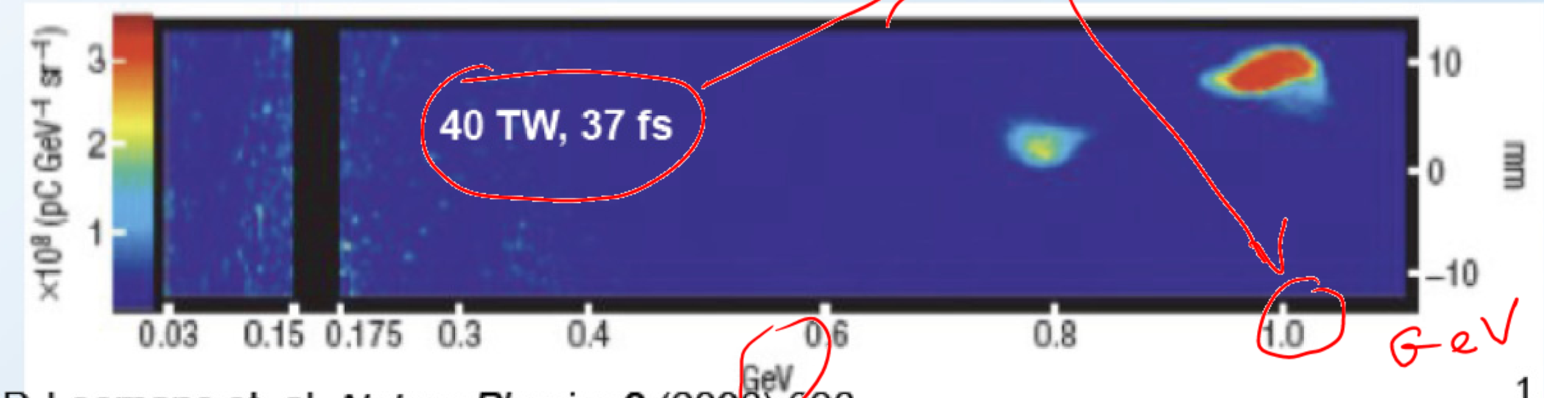
- Use the SLAC injector complex and 2/3 of the SLAC linac to deliver electrons and positrons
  - Compressed 25 GeV beams → ~20 kA peak current
  - Small spots necessary for plasma acceleration studies
- Two separate installations
  - Final bunch compression and focusing system in Sector 20
  - Expanded Sector 10 bunch compressor for positrons



Channel guided laser-plasma accelerator has produced GeV beams

- Higher power laser $\Delta W[\mathrm{GeV}] \sim I[\mathrm{W/cm^2}]/n[\mathrm{cm^{-3}}]$
- Lower density, longer plasma

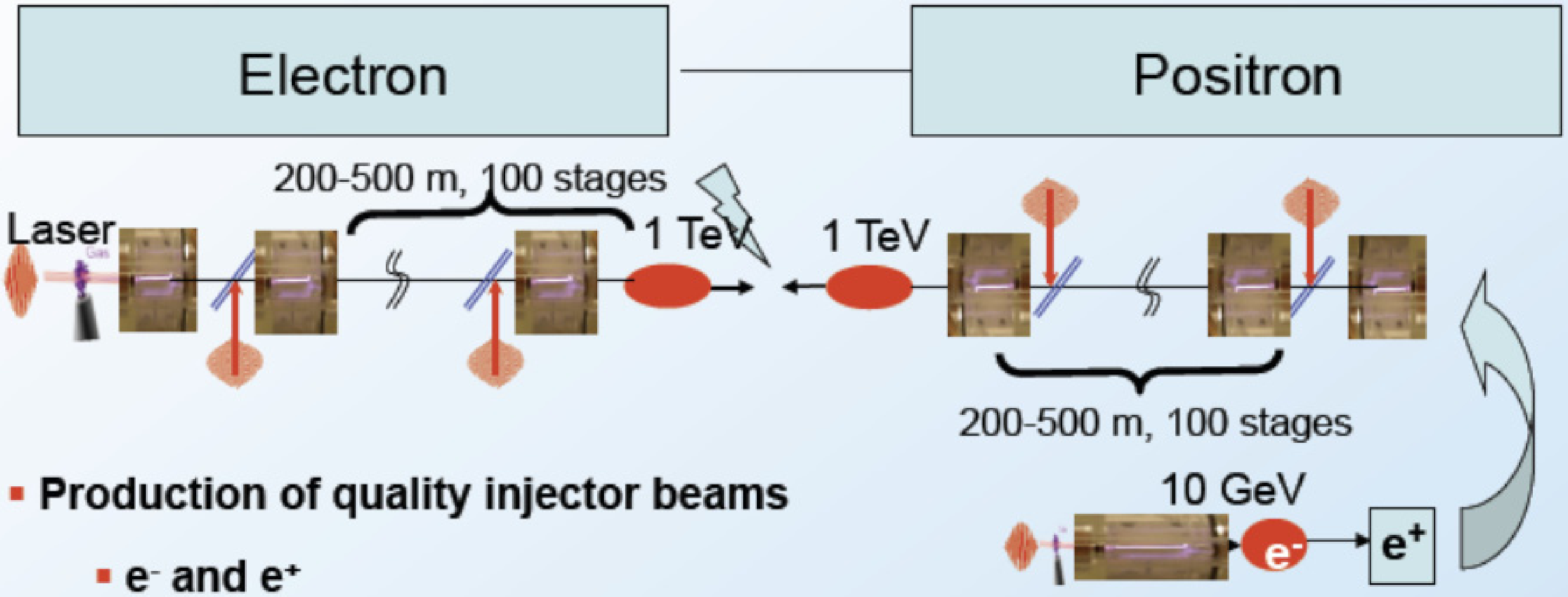




GeV

W.P. Leemans et. al, *Nature Physics* **2** (2006) 696

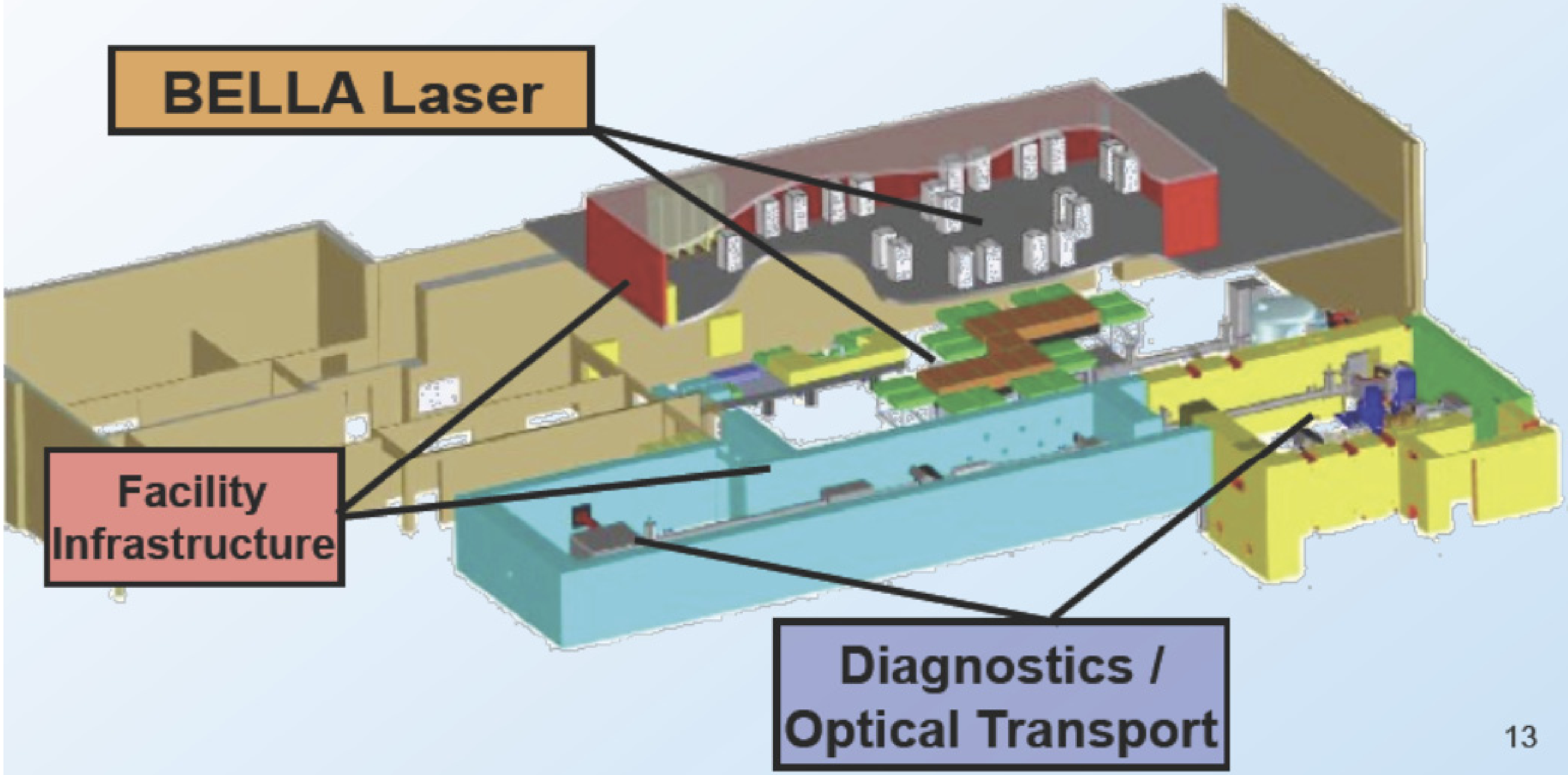
10 GeV module is suitable building block for an LPLC



- **Production of quality injector beams**
  - **e^- and e^+**
- **Linac structure: length, density, channel shape, collisions, emittance,…**
- **Power source: wavelength, pulse energy, pulse duration, pulse shape, focal spot size and shape, rep rate,…**
- **How to handle all this power?**
- **How to focus the beams?**
- **And many more questions…**

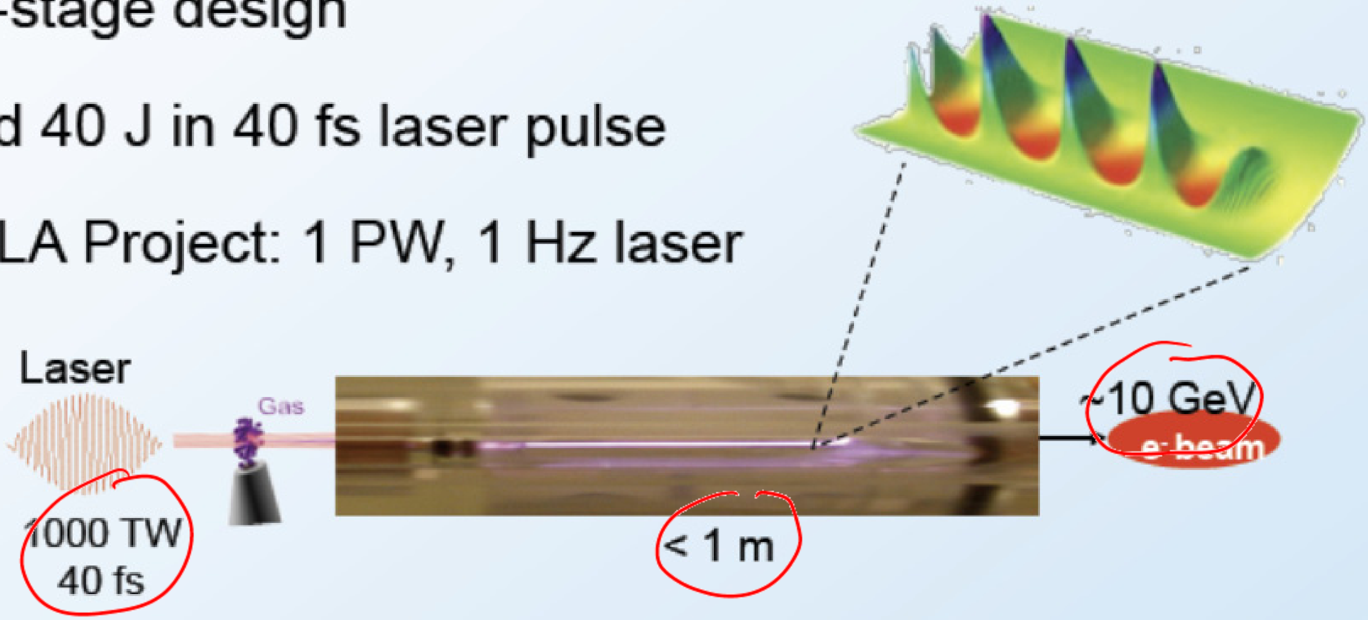
BELLA Project scope

- High rep rate (1 Hz), Petawatt class laser (>40 J in < 40 fs)
- Laser bay and target area
- Laser diagnostics to verify CD-4 goals



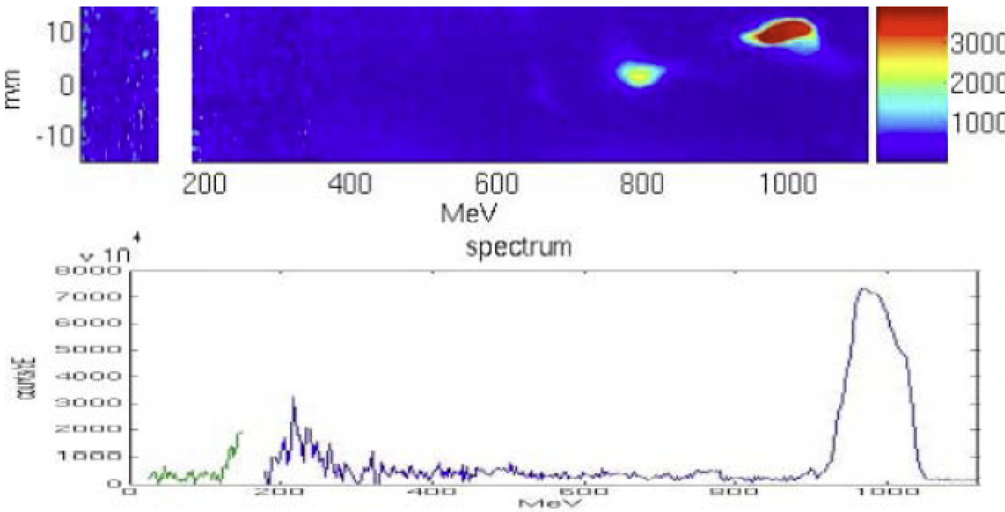
Example of R&D with BELLA -- 10 GeV module

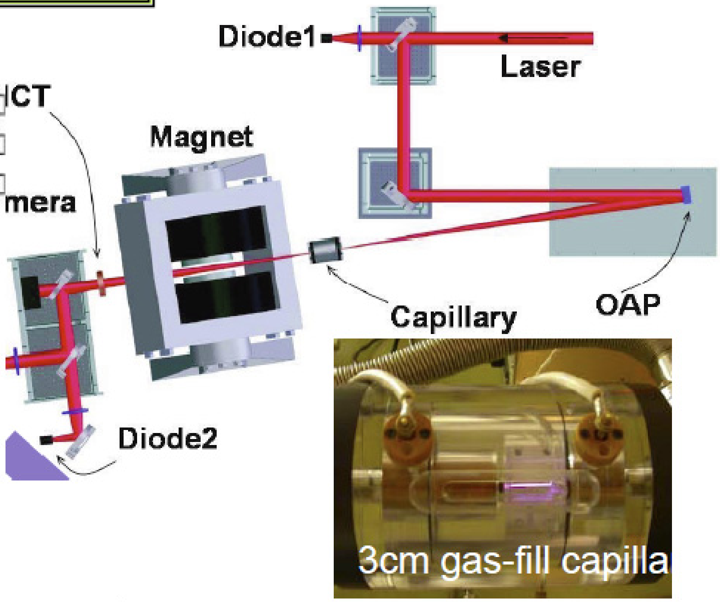
- Two-stage design
- Need 40 J in 40 fs laser pulse
- BELLA Project: 1 PW, 1 Hz laser



- Will be followed by staging at multi-GeV energies with BELLA
- 10 GeV beam will allow positron production experiments

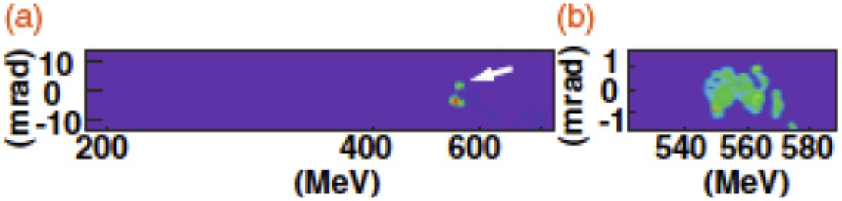
1 GeV capillary accelerator experiment at LBNL/Oxford U.

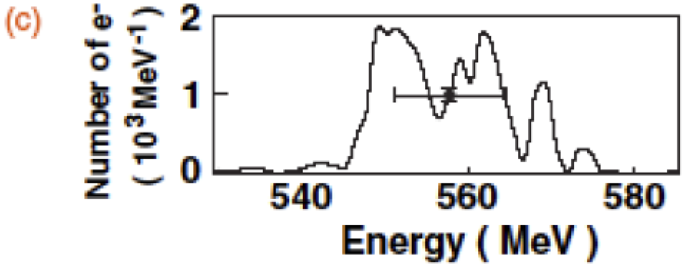


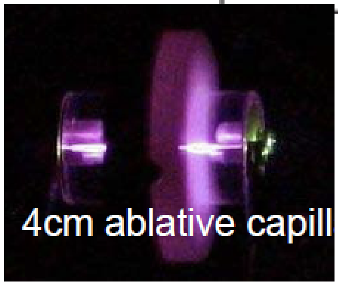


3cm gas-fill capilla

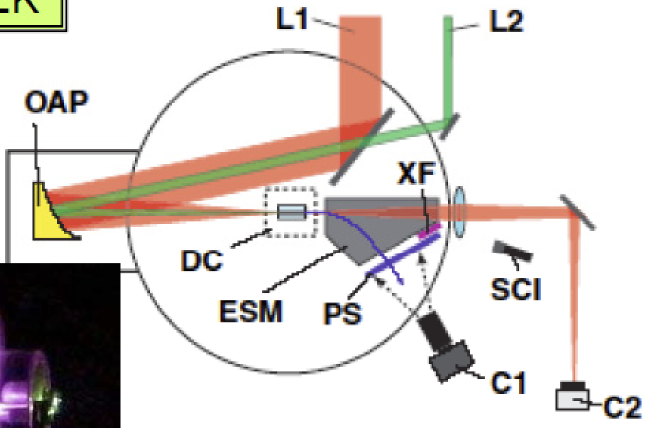
0.56 GeV capillary accelerator experiment at CAEP/KEK





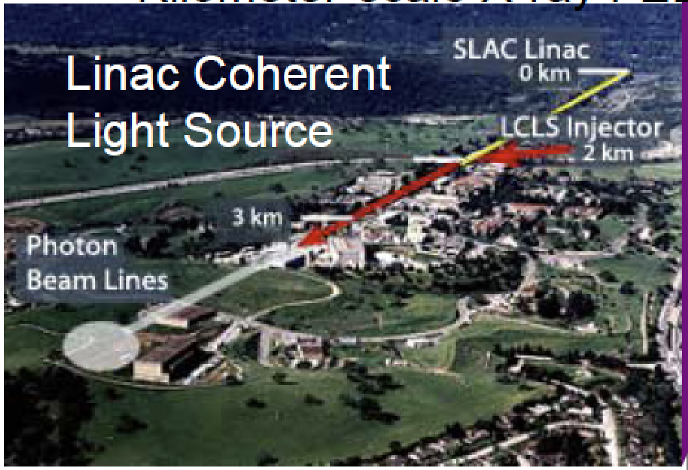


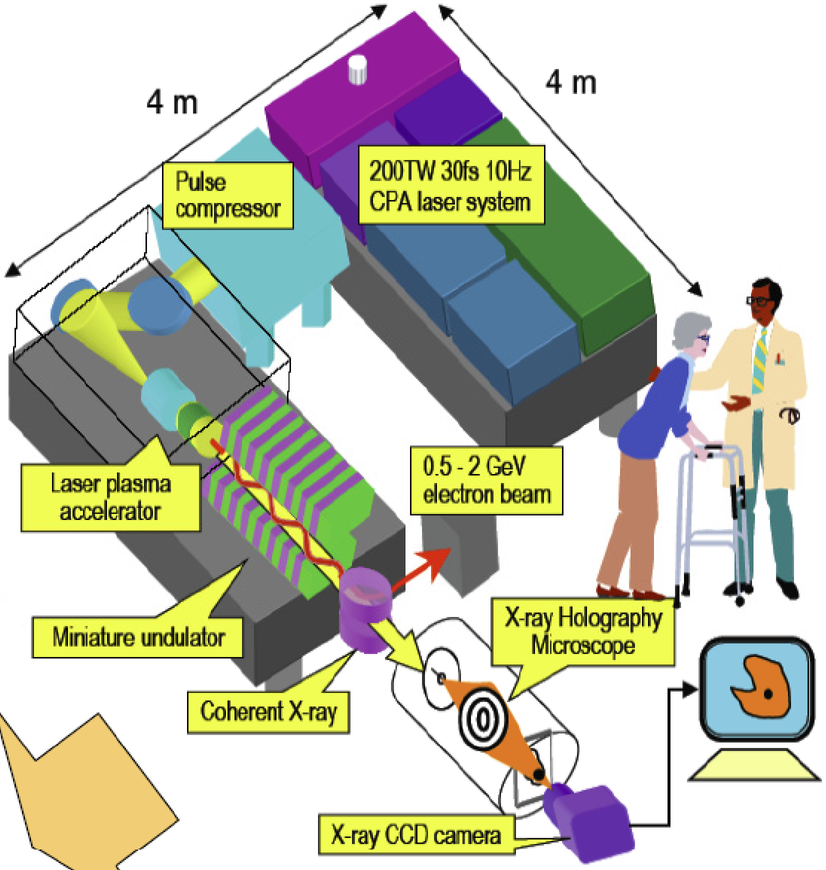
4cm ablative capill



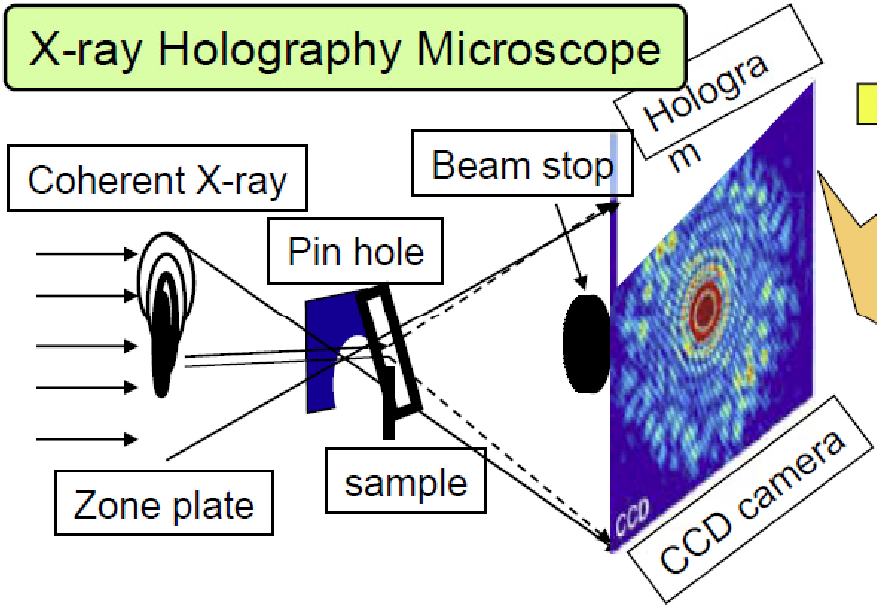
Laser-driven table-top X-ray Free Electron Laser

Kilometer-scale X-ray FEL



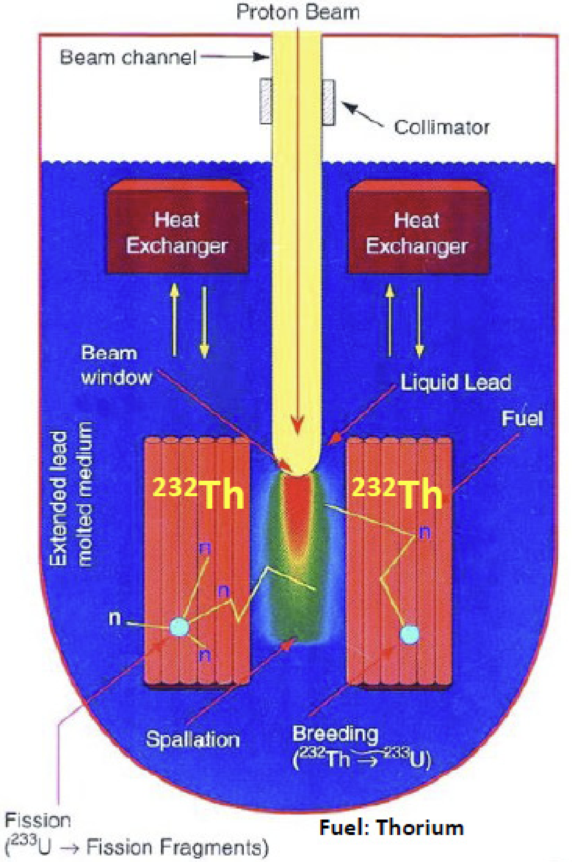


X-ray Holography Microscope



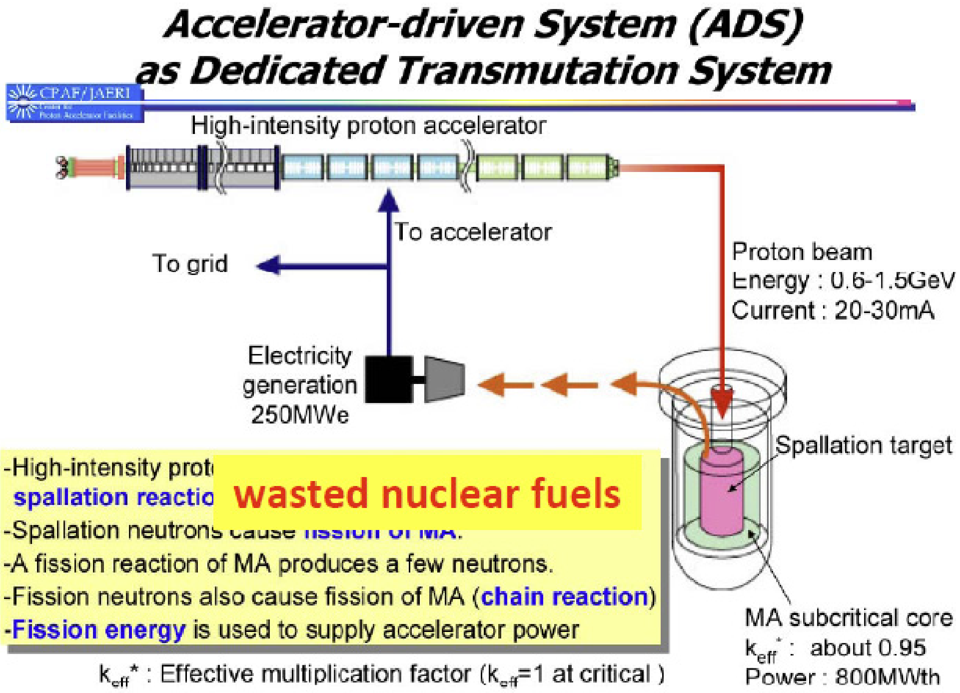
The dream of realizing accelerator driven (subcritical reactor) system and nuclear waste transmutation system comes true with high power superconducting linacs !

Subcritical reactor alone



Fuel: Thorium

Electric power generation & nuclear transmutation



Accelerator-driven System (ADS) as Dedicated Transmutation System

-High-intensity prot
spallation reactio

wasted nuclear fuels

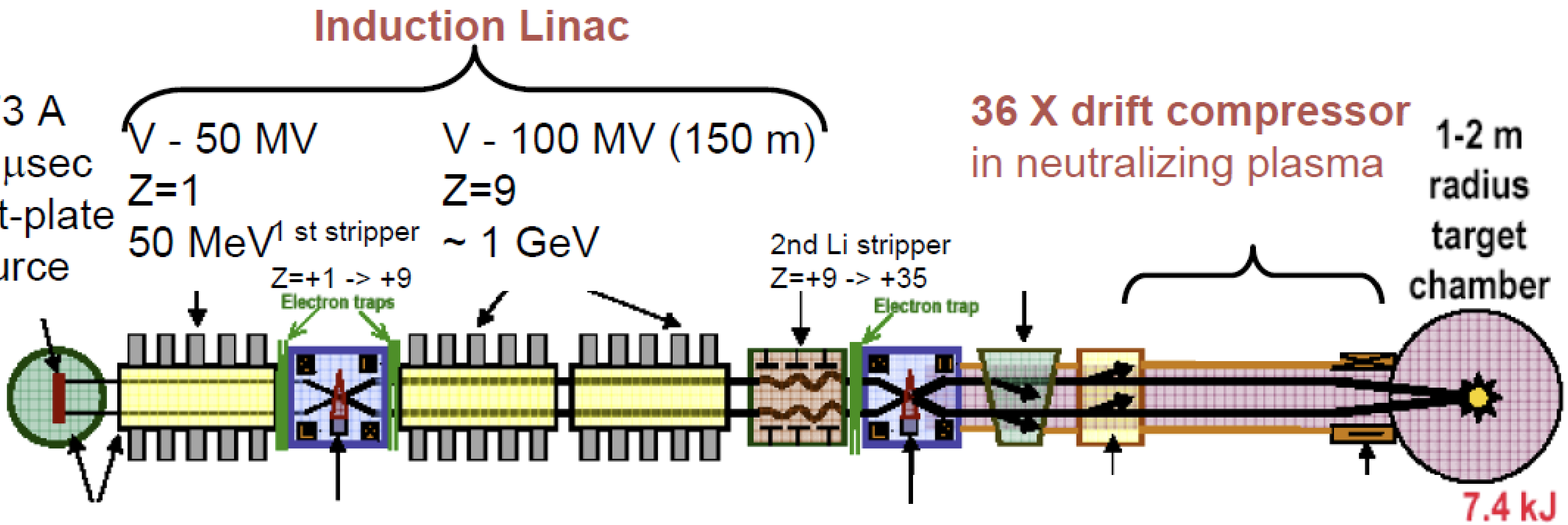
-Spallation neutrons cause **fission of MA**.
-A fission reaction of MA produces a few neutrons.
-Fission neutrons also cause fission of MA (**chain reaction**)
-**Fission energy** is used to supply accelerator power

k_{eff}* : Effective multiplication factor (k_{eff}=1 at critical)

MA: minor actinide

Idea of Proton Driven Inertial Fusion : Down

Driver for Heavy Ion Inertial Fusion Program in US-VNL



Induction Linac

0.73 A
20 µsec
Hot-plate
source

V - 50 MV
Z=1
50 MeV

1 st stripper
Z=+1 -> +9

V - 100 MV (150 m)
Z=9
~ 1 GeV

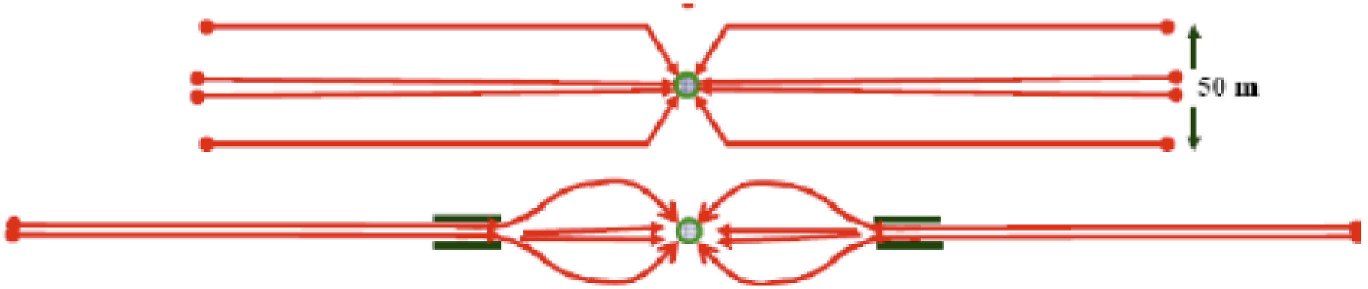
2nd Li stripper
Z=+9 -> +35

36 X drift compressor
in neutralizing plasma

1-2 m
radius
target
chamber

7.4 kJ
per
beam
on
target

Driver configuration (Horizontal)



G.B.Logan (VNL), presented at HIF2008, Tokyo Japan