Colliders - "*Quo Vadis*?" :

Tomorrow and "After Tomorrow"

Analysis, Prediction and Plan

Vladimir Shiltsev

Fermi National Accelerator Laboratory

Accelerator Physics Center

CONTENT

Past

Present

Tomorrow

After Tomorrow

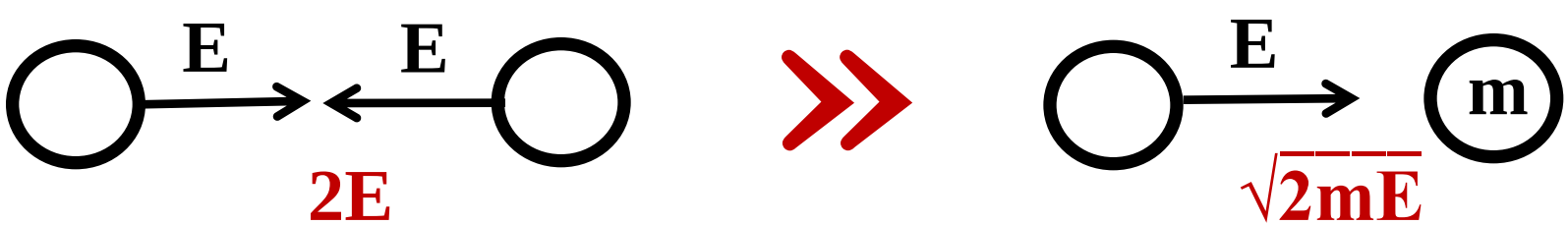
Colliders

Invented in 1956 (if not earlier)

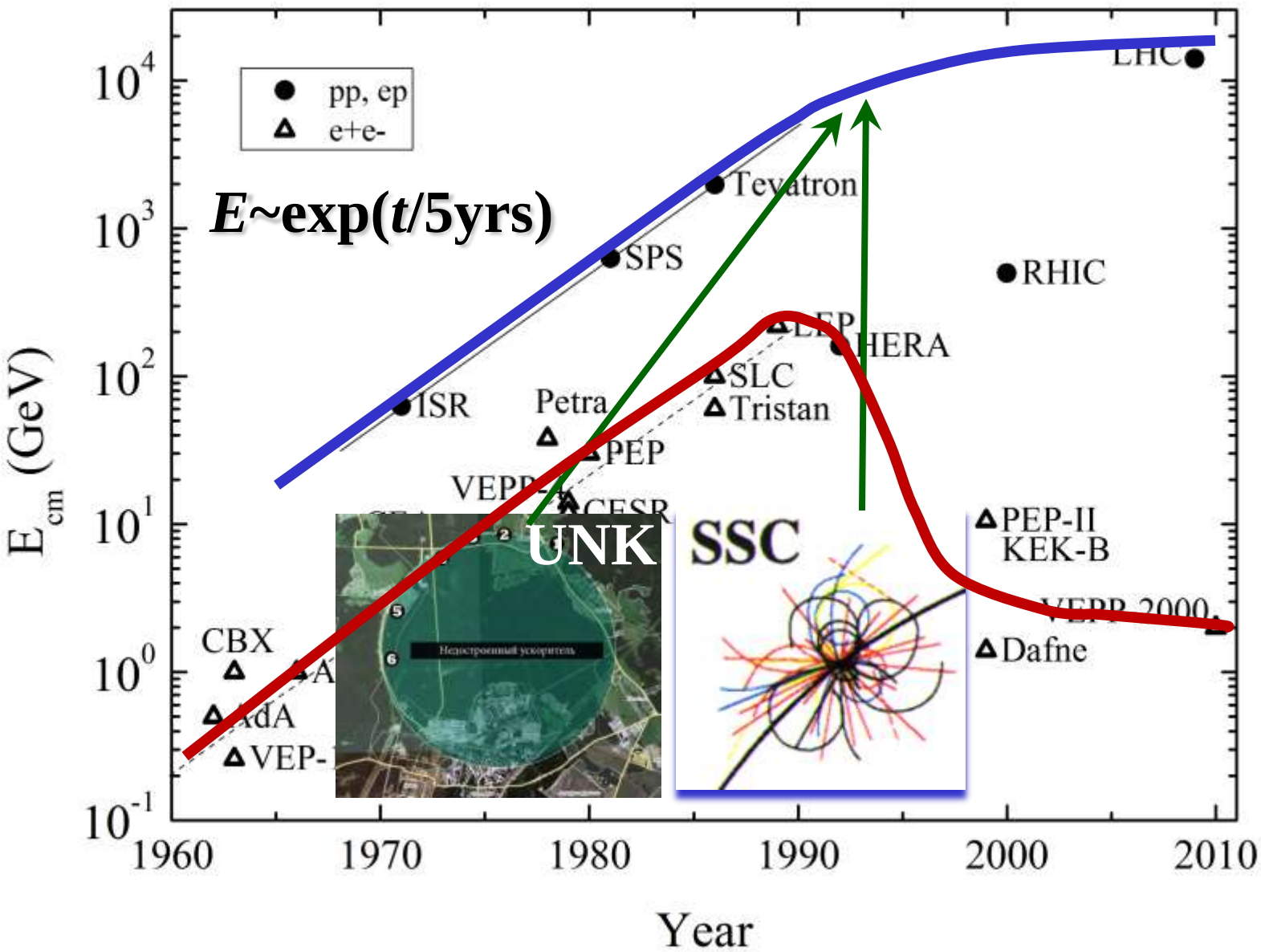
First operational in 1962 (50 years! Hurray!)

"…It is estimated that [since then] accelerator science has influenced almost 1/3 of physicists and physics studies and on average contributed to physics Nobel Prize-winning research every 2.9 years. " **Haussecker&Chao *Physics in Perspective* 13** 146 (2011)

The (only) reason is ENERGY



Colliders: Glorious Past



Colliders: Present – Energy Frontier

Year

Colliders: Operated (Planned)

	early 1990's	early 2010's	2030's
Europe	**HERA, (LHC)** *LEP (Dafne)*	**LHC** (*Super-B*, **HL-LHC, LHeC,** *E***NC**)	**HE-LHE** *CLIC?*
Russia	*VEPP-2, VEPP-4* (**UNK**, *VLEPP*)	***VEPP-2000,VEPP-4M*** (**NICA**, *Tau-Charm*)	**NICA** ? *Higgs Factory* ?
USA	**Tevatron**, (**SSC**) *SLC, CESR*, (*PEP-II*)	**RHIC** (*e***RHIC**, *EL***IC**)	*Muon Collider* ? *PWLA/DLA* ?
Asia	*Tristan, BEPC* (*KEK-B*)	*BEPC* (*Super-KEKB*)	*ILC* ?
Total	9 (7)	5 (9)	1 + ?

Colliders: Present

LHC
- 8 TeV c.m. in *p-p* ~4e33 cm^{-2} s^{-1}; + *ions*
- 12+TeV 1e34 >2014 → 5e34 in 2022 **HL-LHC**

RHIC
- 0.5TeV c.m. polarized *p-p* 1.5e32 $cm^{-2}s^{-1}$,*ions*
- >2022: *e*RHIC with 5(30) GeV ERL *e*-

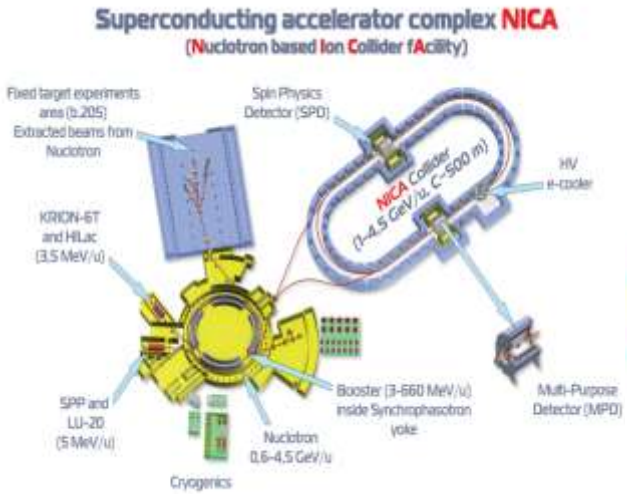
VEPP4
- 3-7 GeV c.m. *e*+*e*- 4e30$cm^{-2}s^{-1}$, dE/E<0.01%

BEPCII
- 2-4.4 GeV c.m. *e*+*e*-, ~1e33$cm^{-2}s^{-1}$ at 3.77GeV

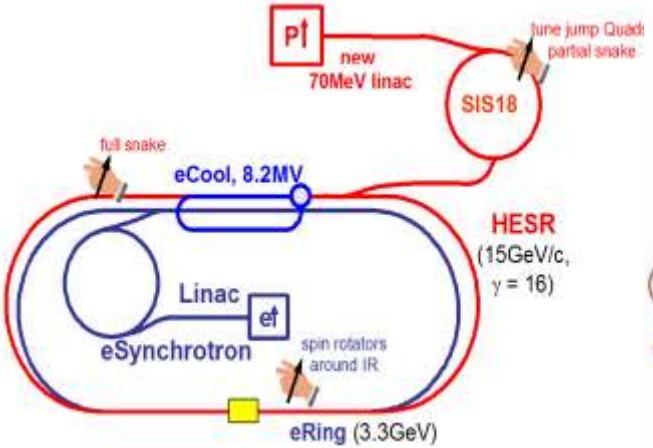
VEPP-2000
- 1-2 GeV c.m. *e*+*e*- 2e31$cm^{-2}s^{-1}$, "round beams"

Colliders for Tomorrow (this decade)

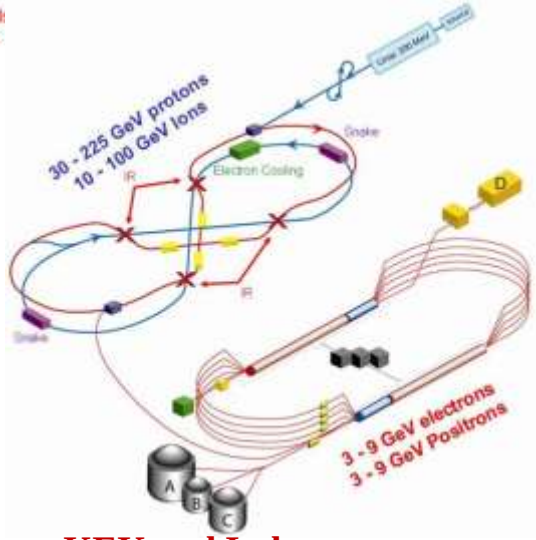
Dubna: 1-4.5 GeV/amu
ion-ion (p,..Au^{+79}) ~10^{27} cm^{-2} s^{-1}



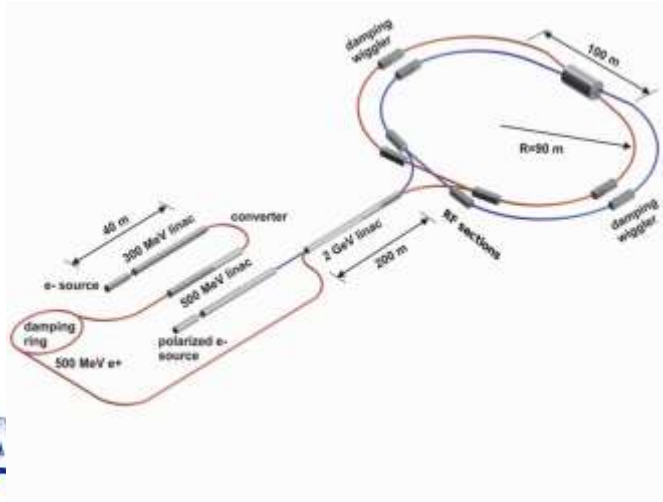
ENC at FAIR: ~15 GeV cm
electron-nucleon ~10^{32} -10^{33}cm^{-2}s^{-1}



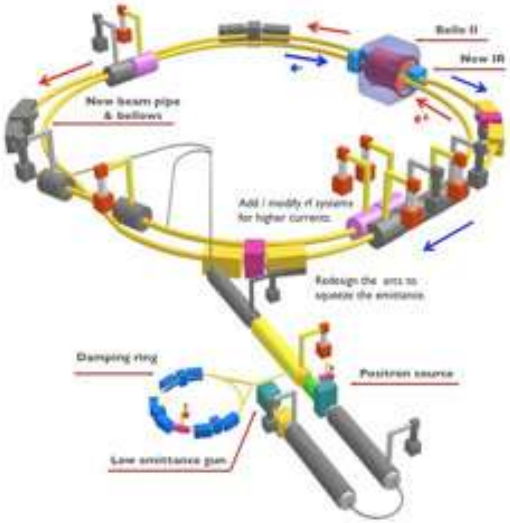
ELIC at JLab: ~50 GeV cm
electron-nucleon ~few 10^{34} cm^{-2}s^{-1}



C-Tau factory in Novosibirsk:
2-5 GeV cm e+e- ~10^{35} cm^{-2}s^{-1}



Asymmetric Super-B Factories at KEK and Italy:
4+7 GeV e+ e-, luminosity ~10^{36} cm^{-2}s^{-1}

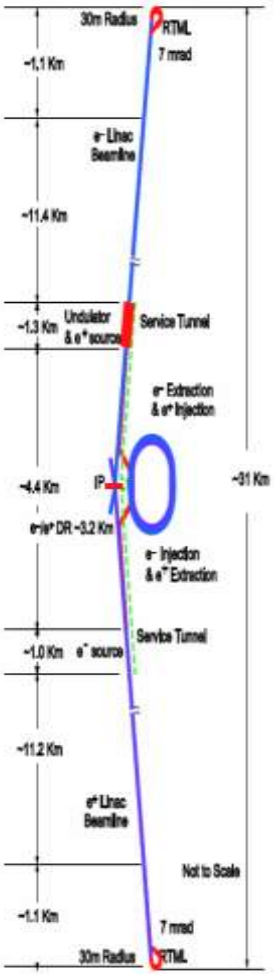


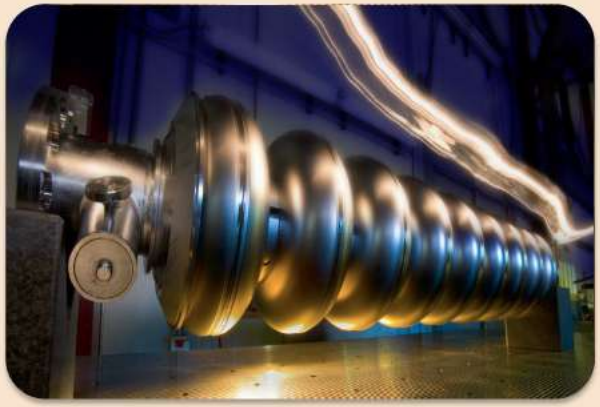
Colliders for Tomorrow (2020's)

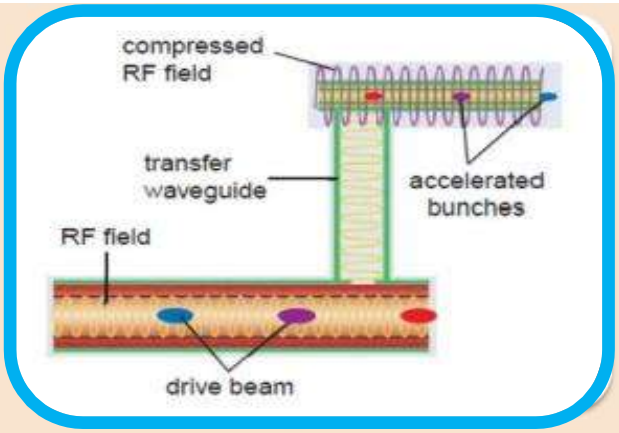
- LHC:
  - high-luminosity LHC (x5 design L)
  - LHeC
- Lepton Colliders
  - ILC
  - CLIC
  - μ+μ- Collider
- Higgs Factory:
  - linac based *e+e-*
  - ring based *e+e- or* μ+μ-

ILC and CLIC

SB2009







ILC (International Linear Collider)

1.3 GHz superconducting RF

500 GeV – 1 TeV

Focus on 500 GeV machine and detector/physics studies but parameter set exists for 1 TeV, as well as physics studies at other energies

Detector R&D and detector concepts (ILC, SiD)

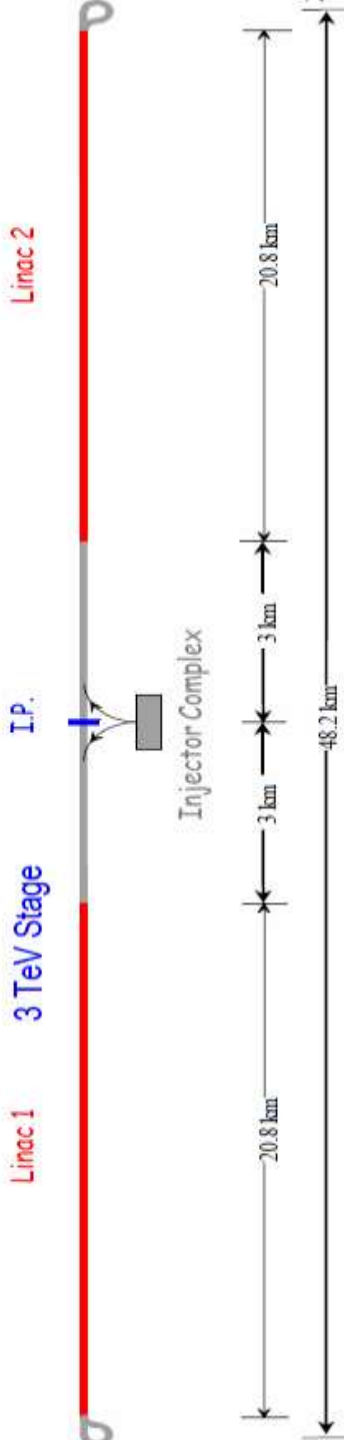
CLIC (Compact Linear Collider)

12 GHz room temperature copper RF, powered by intense drive beam

500 GeV – 1.5 – 3.0 TeV stages

Focus on 3 TeV and parameter set for 500 GeV, intermediate range now being considered – both for accelerator and detectors

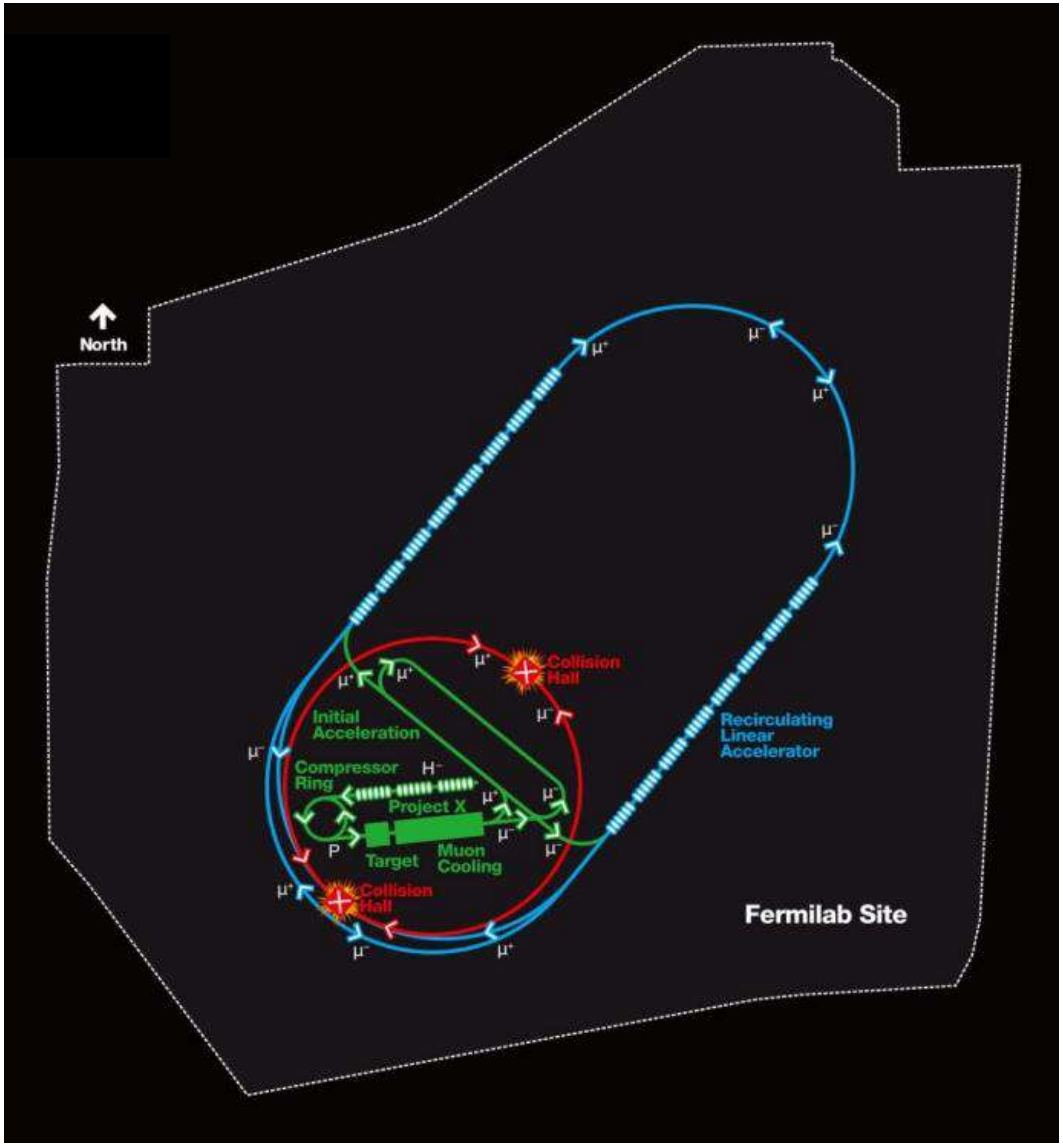
Detector and physics studies carried out for CLIC conditions and adapted detector concepts



Global Design Effort

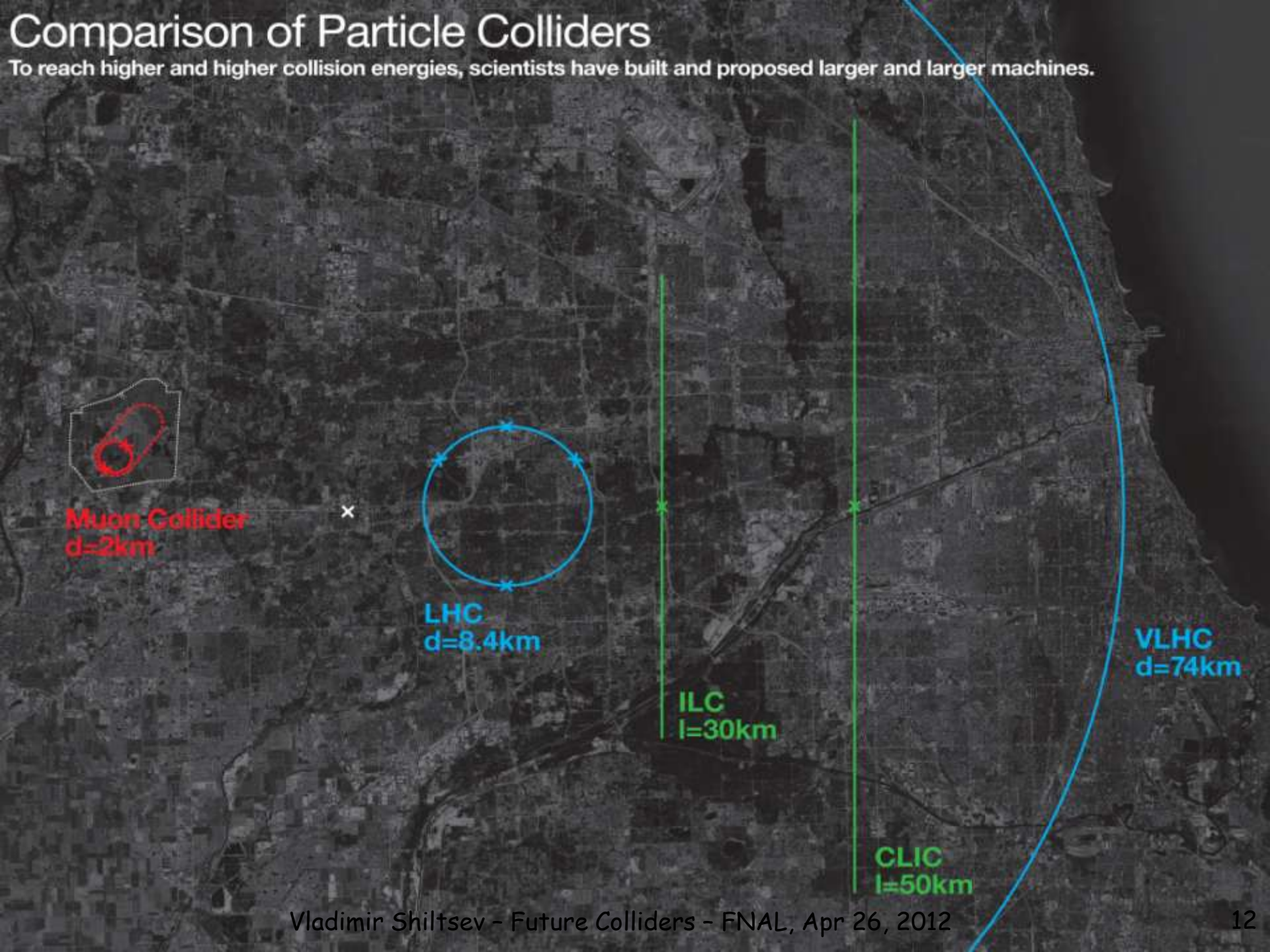
APC

1.5-4 TeV Muon Collider



Comparison of Particle Colliders

To reach higher and higher collision energies, scientists have built and proposed larger and larger machines.



Beamstrahlung

- The average energy loss and the number of photons per electron for the head-on collision with beam energy $E=\gamma mc^2$, bunch charge eN, rms bunch length σ_z, beam size σ_x, σ_y, are given by

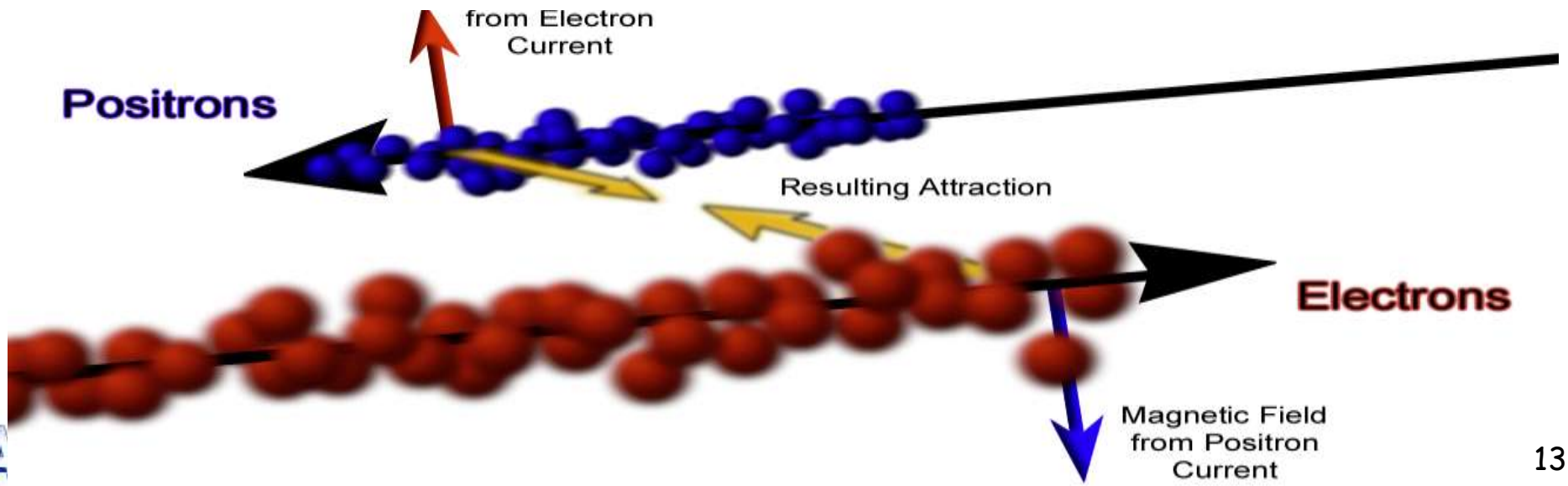
$$\delta_{BS} \equiv \frac{\langle \Delta E \rangle}{E} = 0.864 r_e^3 \gamma \left(\frac{N}{\sigma_z(\sigma_x + \sigma_y)} \right)^2 \sigma_z$$

$$n_\gamma = 2.12 \frac{\alpha r_e N}{\sigma_x + \sigma_y}$$

BB Field

integration length

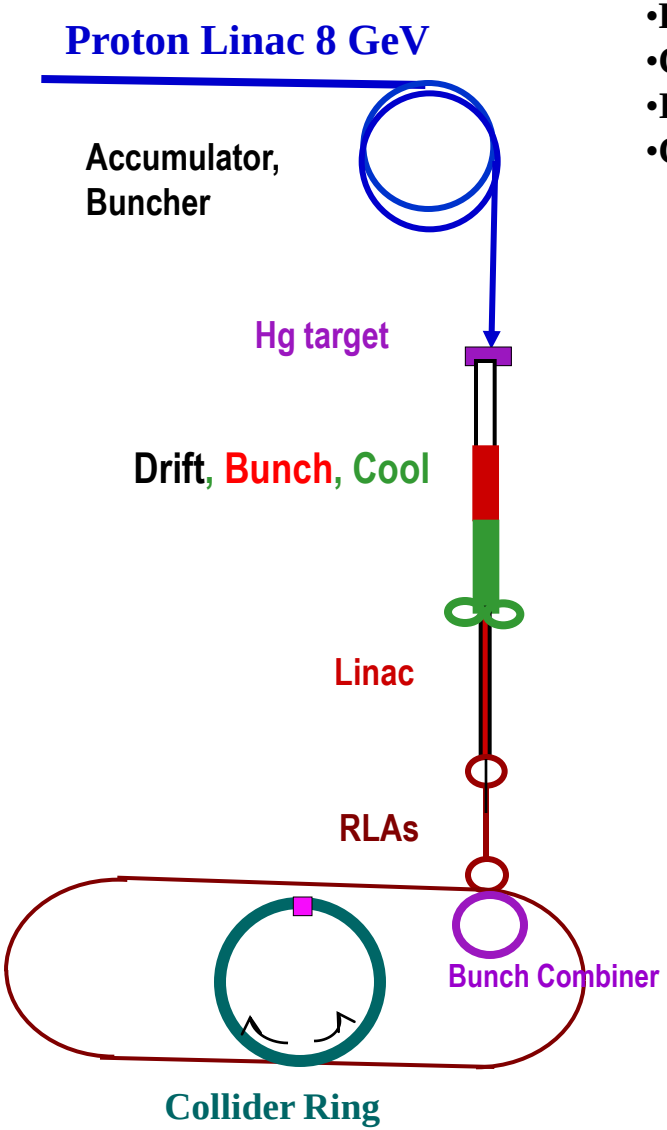
- For flat beams, $\sigma_x + \sigma_y \sim \sigma_x$



Lepton Colliders: Alternatives

	ILC	CLIC	MC
c.m energy, TeV	0.5	3	1.5-4
c.m. dE/E, rms	~2%	>5%	~0.1%
Luminosity , $cm^{-2}s^{-1}$	$2\cdot10^{34}$	$2\cdot10^{34}$ *	few 10^{34}
Feasibility report	2007	2012	2014-16
Technical design	2013	2016	~2020
Number of elements	38,000	260,000	10,000
Hi-Tech length, km	36	~60	14-20
Wall plug power, MW	230	560	120-200
Cost, a.u.	**15-20**	**15-20**	**7-10 ?**

"~NoCooling" Muon Collider



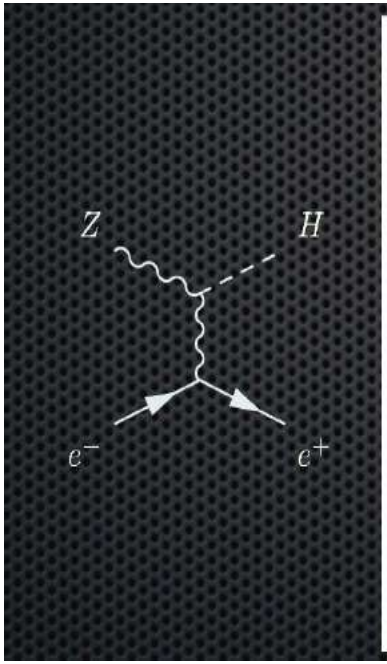
$\delta\nu_{BB}$ =0.0014

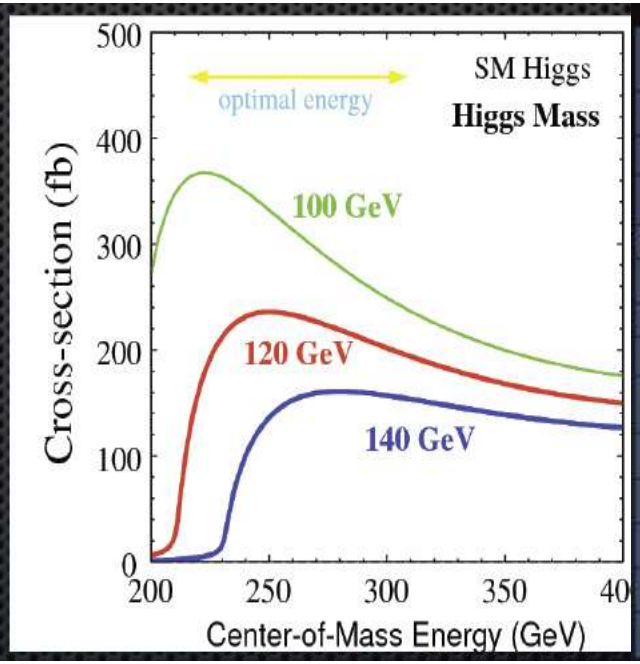
- Reduce transverse emittance to 0.001m
- Could then use 1300MHz ?
- IR quads less than r =10cm
- Combine 12 bunches to 1

D.Neuffer (2011)

Parameter	Symbol	Value
Proton Beam Power	P_p	2.4 MW
Bunch frequency	F_p	60 Hz
Protons per bunch	N_p	3×10^{13}
Proton beam energy	E_p	8 GeV
Number of muon bunches	n_B	1
$\mu^{+/-}$/ bunch	**N_μ**	**10^{12}**
Transverse emittance	**$\varepsilon_{t,N}$**	**0.001m**
Collision β^*	β^*	0.04m
Beam size at collision	$\sigma_{x,y}$	**0.0063cm**
Beam size (arcs)	$\sigma_{x,y}$	0.3cm
Beam size IR quad	σ_{max}	3cm
Collision Beam Energy	$E_{\mu+},E_{\mu-}$	1 TeV (2TeV total)
Luminosity	L_0	1.2×10^{32}

240-250 GeV com *e*+*e*- Higgs Factory

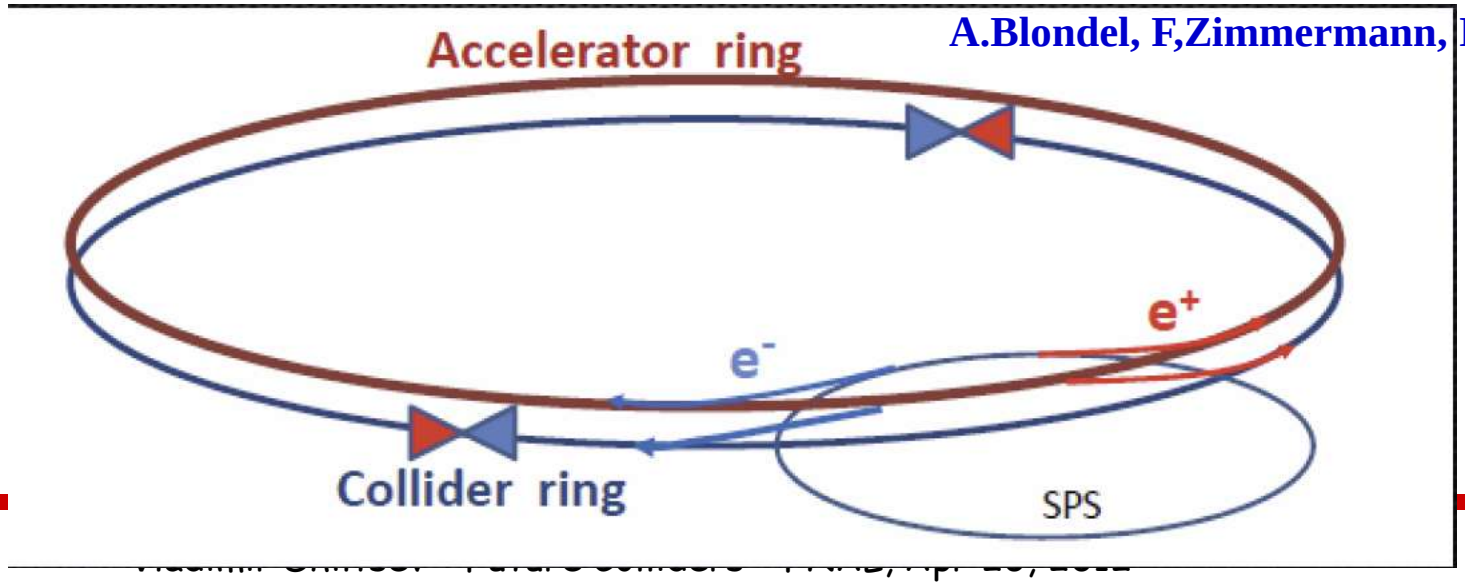




Parameters Example

	TRISTAN	KEKB	LEP2	LEP3	DLEP	SuperTRISTAN 40	SuperTRISTAN 60	
Beam Energy	32	8 / 3.5	105	120	120	120	120	GeV
Circumference	3	3	27	27	53	40	60	km
Beam Current / beam	7	1400 / 1700	4	7.2	14.4	8.6	8.6	mA
Bunches / beam	2	1600	4	3	60	12	18	
β* x / y	2000 / 40	1200 / 6	1500 / 65	150 / 1.2	200 / 2	80 / 2.5	80 / 2.5	mm
Emittances x / y		18 / 0.1	48 / 0.25	20 / 0.15	5 / 0.05	23.3 / 0.09	24.6 / 0.09	nm
Bunch length	10	6	3	3	1.5	3	3	mm
Beam-beam parameters	0.02 0.025	0.05 0.09	0.025 0.065	0.126 0.13	0.1 0.1	0.05 0.156	0.045 0.155	
Radiation loss / turn	300	4 / 2	2750	6900	3470	3420	2150	MV
RF Voltage	400	10 / 5	3640	9000	4600	5000	3300	MV
RF frequency	508	509	352	1300	1300	1300	1300	MHz
Total SR Power	4.2	5.6 / 3.4	22	100	100	59	37	MW
Luminosity / IP	0.04	21	0.13	13	16	10	10	/nb/s

A.Blondel, F,Zimmermann, K,Oide



40 km e+e- Higgs Factory Super TRISTAN

K,Oide

e+e- HF Dilemma: Performance

Ring or Linear?

Technology: Matured & Experienced	Ring >>> Linear	
Robustness on Luminosity	Ring >> Linear	Remember SLC.
Beamstrahlung-free	Ring ≥ Linear ?	Needs detailed calculation
Electron Cloud-free	Ring >>> Linear	
Sources	Ring >> Linear	
Polarization	Linear > Ring	
ϒϒ option	Linear >>> Ring	No solution known for ring.
Extendability	Ring: Hadron Collider Linear: Higher Energy by a different scheme	Both require significant investment.

K.Oide

e+*e*- HF Dilemma: Cost & Power

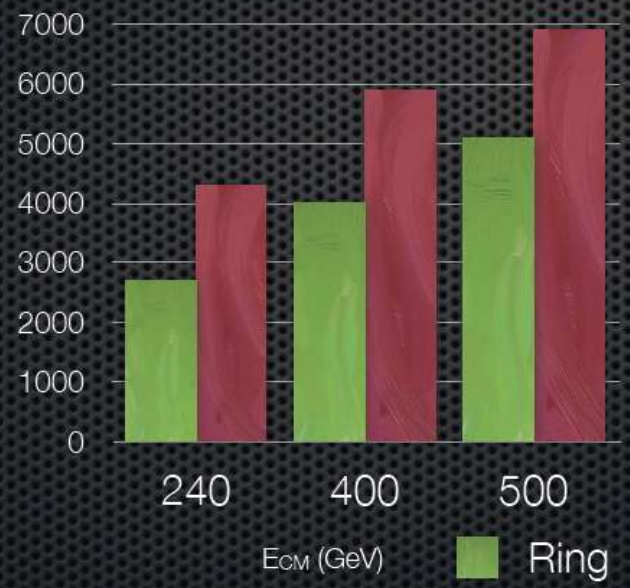
Ring or Linear?

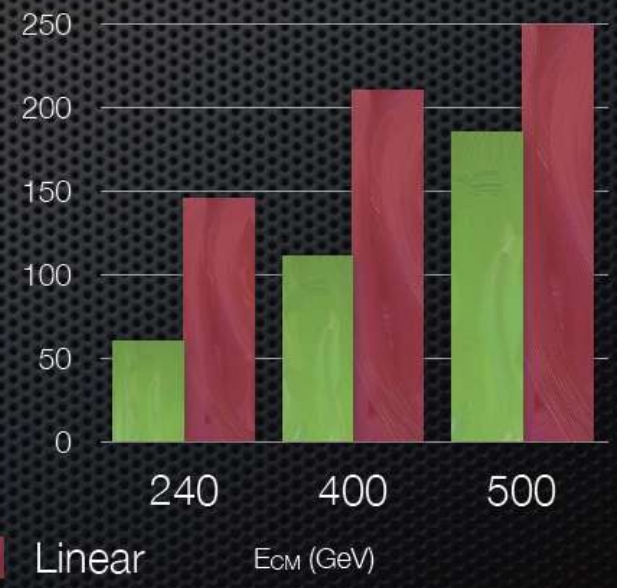
Construction

E_{CM} (GeV)	Ring	Linear
240	2700	4300
400	4000	5900
500	5090	6900

Site Power (MW)

E_{CM} (GeV)	Ring	Linear
240	60	146
400	111	210
500	185	250





K.Oide

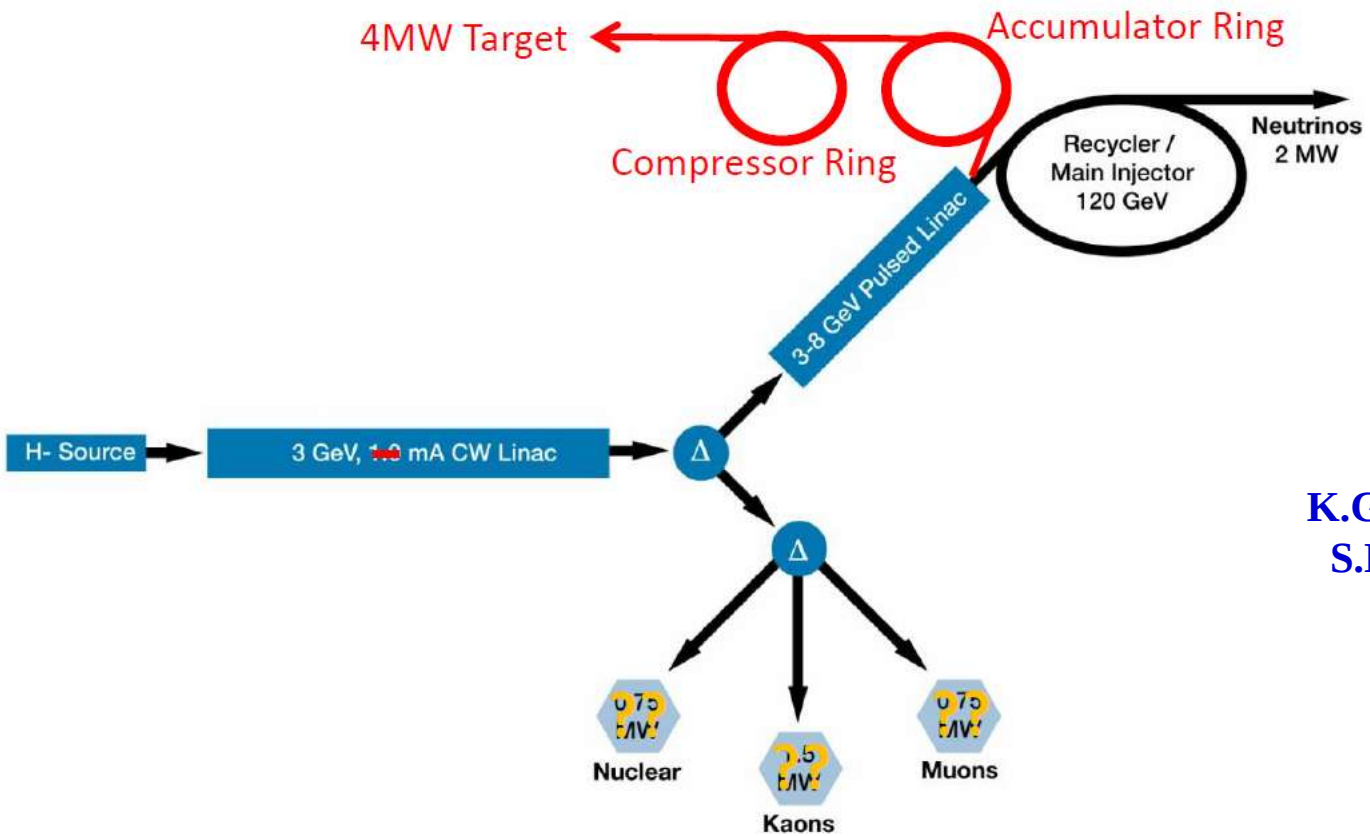
μμ Higgs Factory ca 1999: 10^{31} at dE/E=0.003%

PRST-AB 2 CHARLES M. ANKENBRANDT *et al.* 081001 (1999)

TABLE I. Baseline parameters for high energy and low energy muon colliders. Higgs/yr assumes a cross section $\sigma = 5 \times 10^4$ fb; a Higgs width $\Gamma = 2.7$ MeV, 1 yr $= 10^7$ s.

COM energy (TeV)	3	0.4		0.1	
p energy (GeV)	16	16		16	
p's/bunch	2.5×10^{13}	2.5×10^{13}		5×10^{13}	
Bunches/fill	4	4		2	
Rep. rate (Hz)	15	15		15	
p power (MW)	4	4		4	
μ/bunch	2×10^{12}	2×10^{12}		4×10^{12}	
μ power (MW)	28	4		1	
Wall power (MW)	204	120		81	
Collider circum. (m)	6000	1000		350	
Ave bending field (T)	5.2	4.7		3	
rms $\Delta p/p$ (%)	0.16	0.14	0.12	0.01	0.003
6D $\epsilon_{6,N}$ $(\pi \mathrm{m})^3$	1.7×10^{-10}	1.7×10^{-10}	1.7×10^{-10}	1.7×10^{-10}	1.7×10^{-10}
rms ϵ_n (π mm mrad)	50	50	85	195	290
β^* (cm)	0.3	2.6	4.1	9.4	14.1
σ_z (cm)	0.3	2.6	4.1	9.4	14.1
σ_r spot (μm)	3.2	26	86	196	294
σ_θ IP (mrad)	1.1	1.0	2.1	2.1	2.1
Tune shift	0.044	0.044	0.051	0.022	0.015
n_{turns} (effective)	785	700	450	450	450
Luminosity ($\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$)	7×10^{34}	10^{33}	1.2×10^{32}	2.2×10^{31}	10^{31}
Higgs/yr			1.9×10^3	4×10^3	3.9×10^3

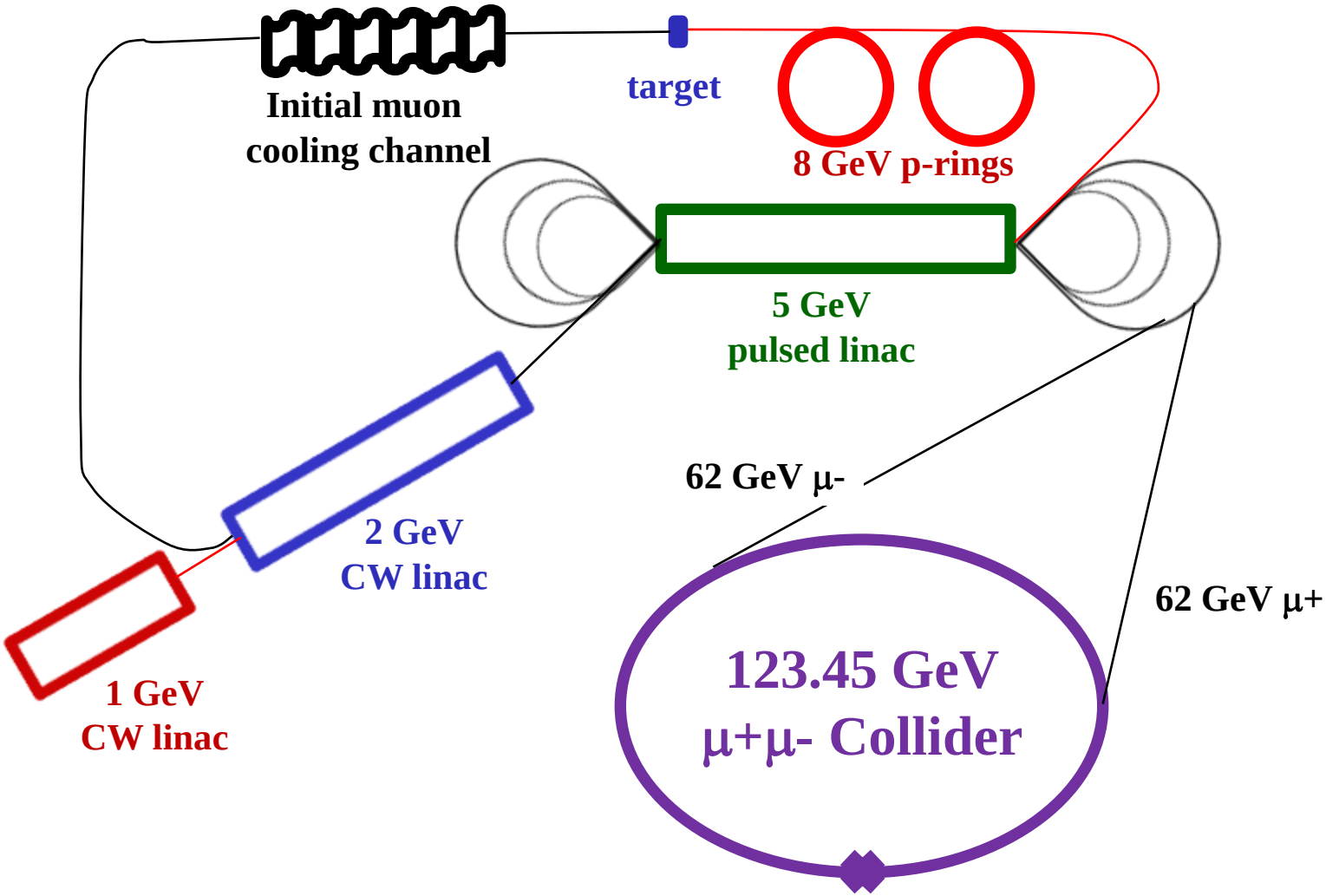
Muon Production by Project X



K.Gollwitzer
S.Nagaitsev

- A plausible upgrade path to 4 MW at 8 GeV for Project X exists and includes:
  - increasing the beam current during the injection pulse to 5 mA (10 mA peak);
  - increasing the rep. rate to 15 Hz;
  - increasing the beam pulse length to 6.7 ms (10% duty cycle).
- Such an upgrade would reuse > 75% of RDR cost.

Project-X based Muon Higgs Factory



Cost range: 0.5+0.5+0.5+0.5+0.5+0.5 = 3-6 Units (incl. Project X)

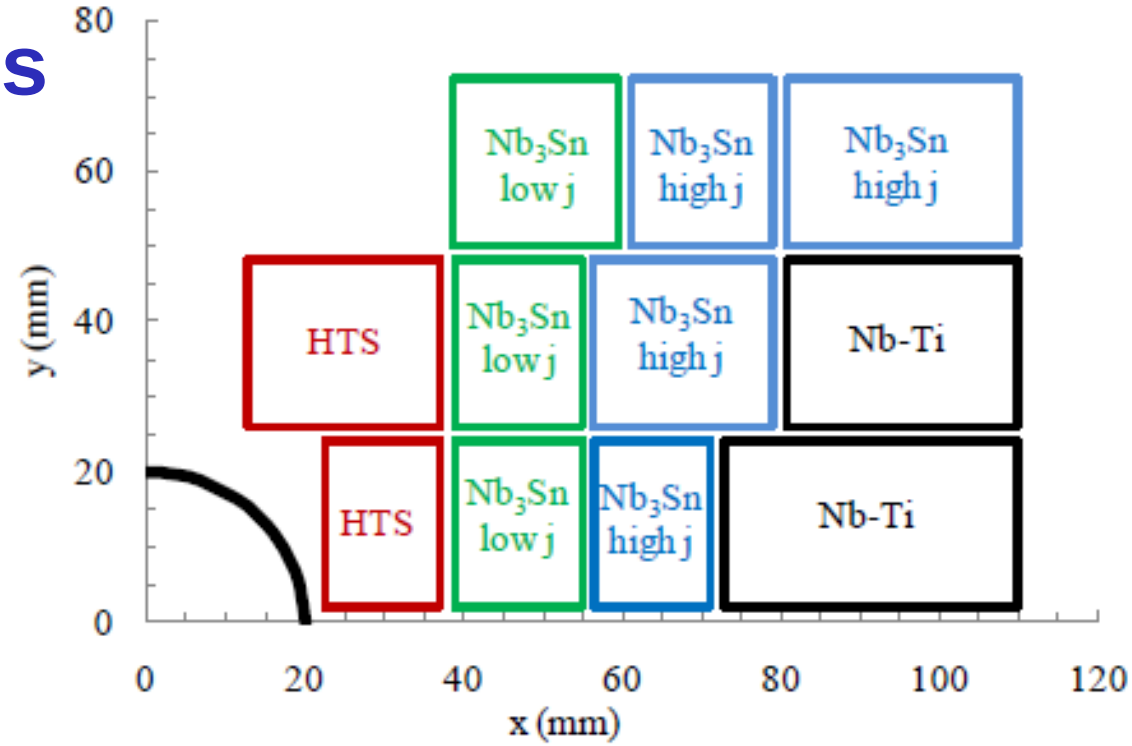
"Cheap" $\mu+\mu-$ HF: Luminosity

Parameter	Symbol	"Conservative"	"Stretched"
Proton Beam Power	P_p	2.4 MW	4 MW
Bunch frequency	F_p	15 Hz	15 Hz
Protons per bunch	N_p	1.2×10^{14}	2×10^{14}
Proton beam energy	E_p	8 GeV	8 GeV
Number of muon bunches	n_B	1	1
Transverse emittance	$\varepsilon_{t,N}$	**3000 μm**	**1000 μm**
Transverse acceptance	$A_{t,N}$	**300 μm**	**3000 μm**
$\mu^{+/-}$/ bunch	N_μ	**5×10^{10}**	**8×10^{12}**
Collision β^*	β^*	**0.15m**	**0.15m**
Collision energy spread	dE/E	**0.03%=0.0003**	**0.03%=0.0003**
Collision Beam Energy	$E_{\mu+}, E_{\mu-}$	**62 GeV (per beam)**	**62 GeV (per beam)**
Ring Magnetic field	B	**10 T**	**10 T**
Avg Luminosity	<L>	**3×10^{29}**	**2×10^{31}**
Cost	**a.u.**	**3**	**5**

High Energy LHC

20T SC magnets

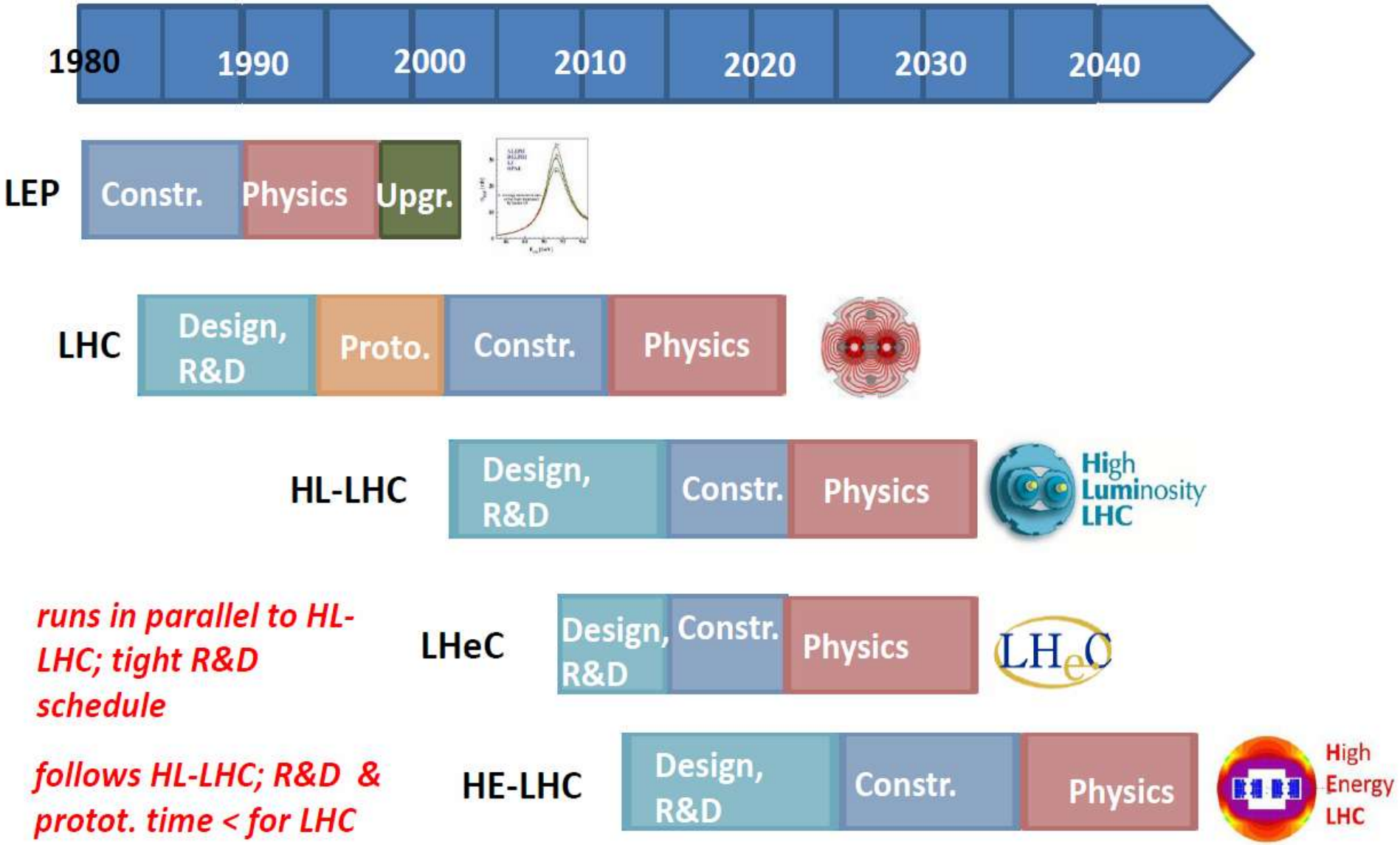
Nb-Ti	26%
Nb3Sn -h	35%
Nb3Sn -l	23%
HTS (Bi2212)	17%



- HE-LHC:
  - 33 TeV c.m. *p-p*, equiv ions
  - $2 \cdot 10^{34}$
  - 6-10 B$?

L.Rossi
E.Todesco
L.Bottura

time line of CERN HEP projects



Source: L. Rossi. LMC 2011 (modified)

Let's Talk About

"After Tomorrow"

~2030's

& evaluate our options

Scale of Numbers

- World's Total GDP ~65,000 B$
- World's Total R&D ~1,300 B$
  - that is ~2% of the above
- World's Basic Sciences ~250 B$
  - that is ~18% of the above
- World's Particle Physics ~3 B$
  - that is ~1.2% of the above

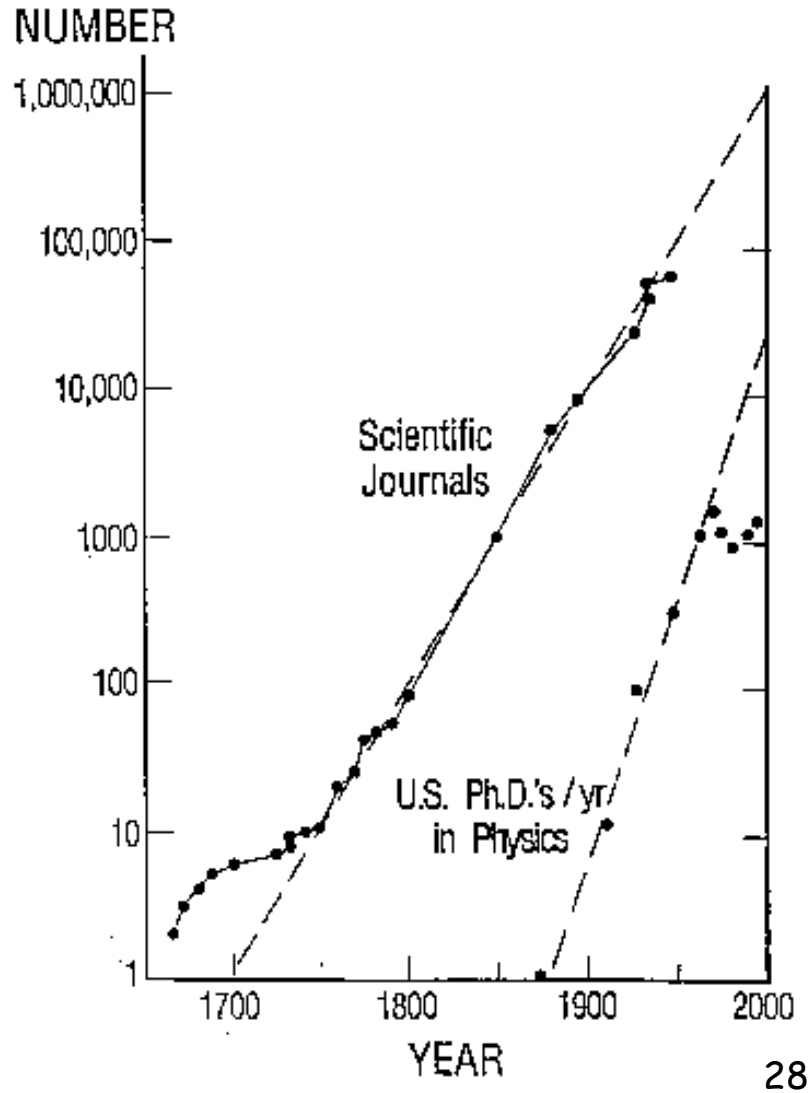
Quite generous for <10,000 scientists

Assume No More "Good Old Times"

The Big Crunch *by David Goodstein* (1994)

The long era of exponential expansion ended decades ago, but we have not yet reconciled ourselves to that fact. The present social structure of science ... evolved during the period of exponential expansion, before The Big Crunch. They are not suited to the unknown future we face. Today's scientific leaders, in the universities, government, industry and the scientific societies are mostly people who came of age during the golden era, 1950 - 1970. We think those were normal times and expect them to return But we are wrong. Nothing like it will ever happen again. Those of us who have gained so much from the era of scientific elites and scientific illiterates must learn to face reality, and admit that those day are gone forever....

From the mode of "each professor in a research university turns out 15 Ph.D's, most of those wanting to become research professors and turn out 15 more Ph.D's" to "life within the limits".



Collider Projects: Cost Categories

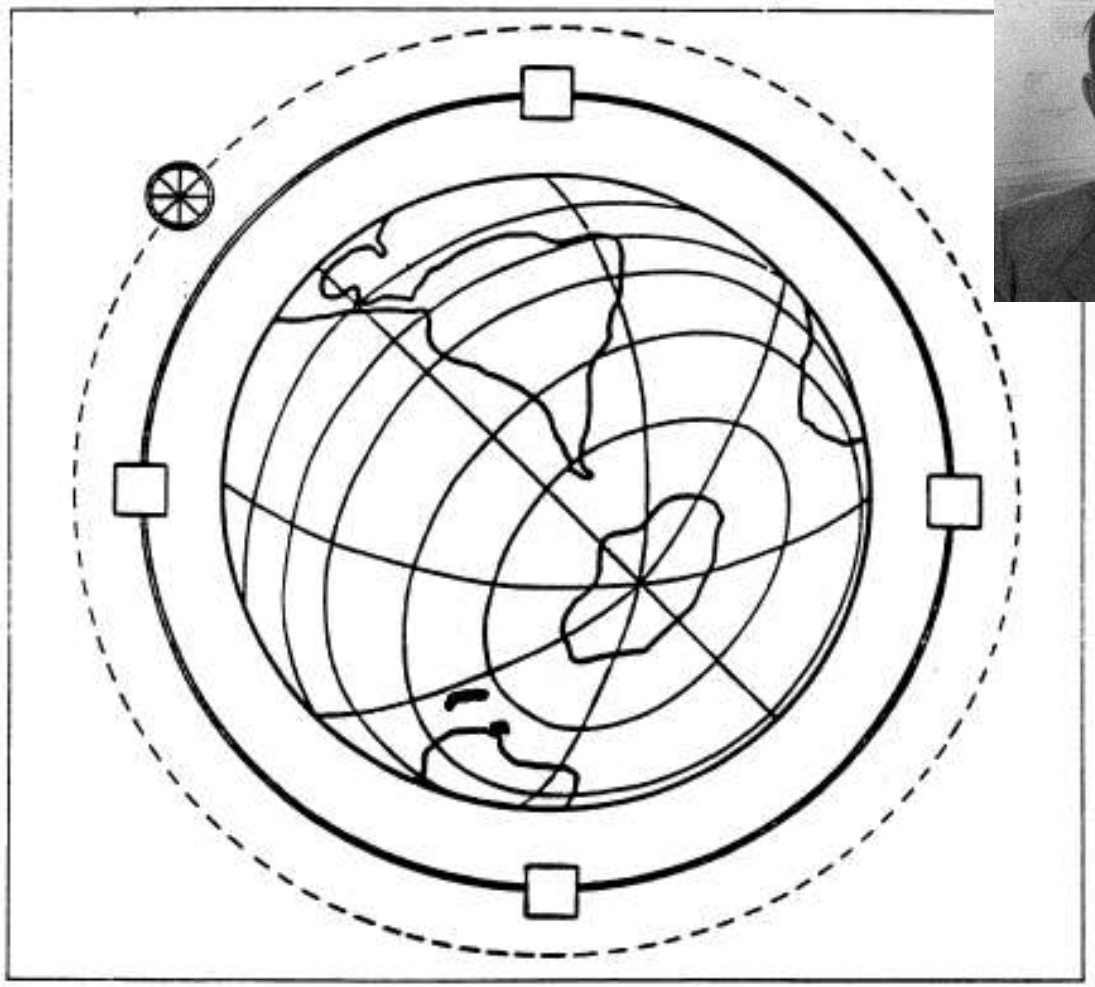
< 0.3 B$	NICA, ENC
0.3-1 B$	Super-*B* factories, eRHIC, Tau-Charm factory, ELIC
1-3 B$	Higgs factory-ring, HL-LHC
3-10 B$	LHeC, Muon Collider, Higgs factory-LC; HE-LHC
10-30 B$	ILC, CLIC

Defining the "Phase-Space"

- "Interesting Physics"
  - *Physics* ∝ log(*Energy*)
  - 100-1000+ TeV (10-100 × LHC)
  - decent luminosity
- "Live within our means":
  - < 10 B$
  - < 10 km
  - < 10 MW (beam power, ~100MW total)

An Example of "Over the Limit"

- "globaltron"
  - 40,000 km
  - >> 1000 B$

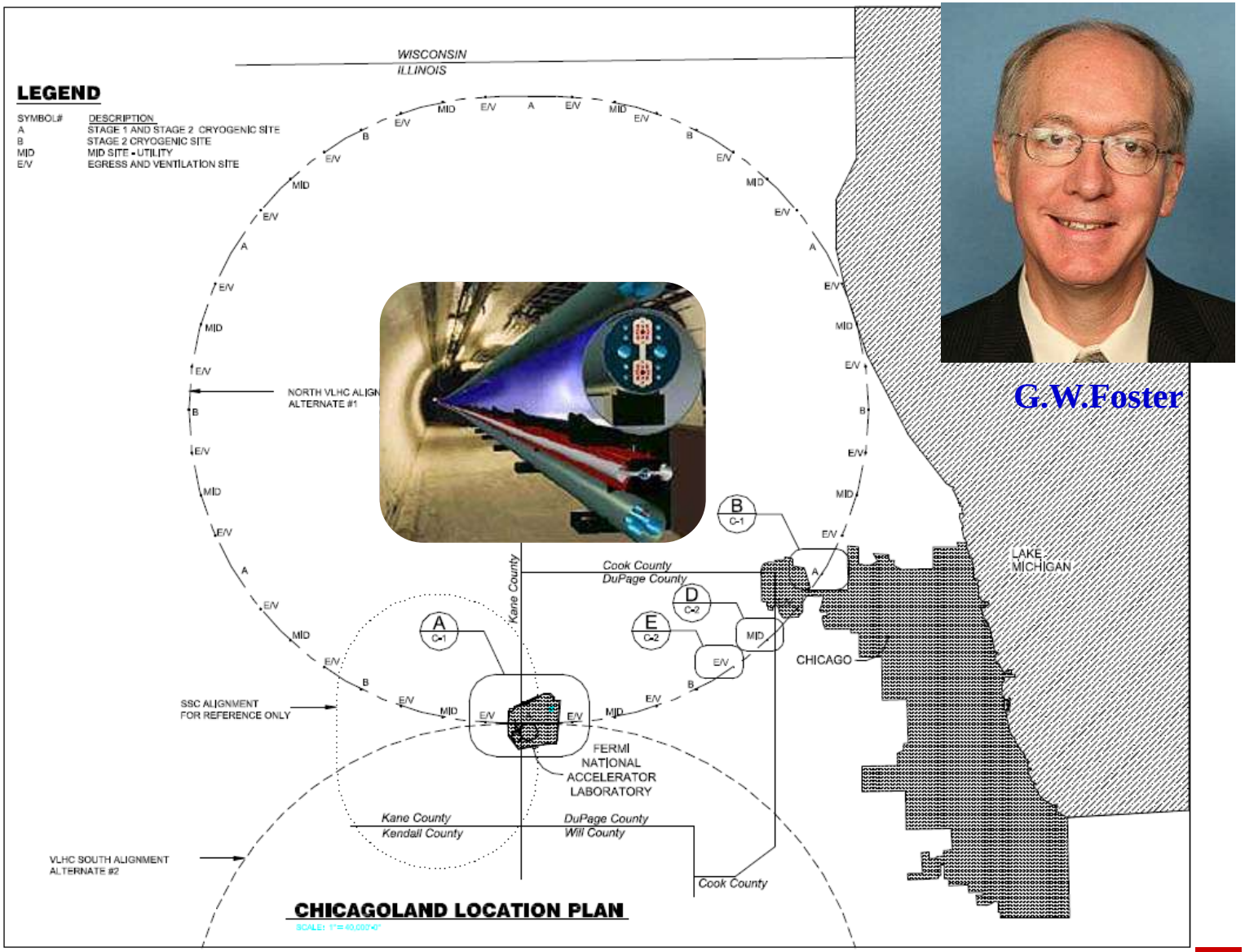


From a 1954 Slide by Enrico Fermi, University of Chicago Special Collections.

E.Fermi

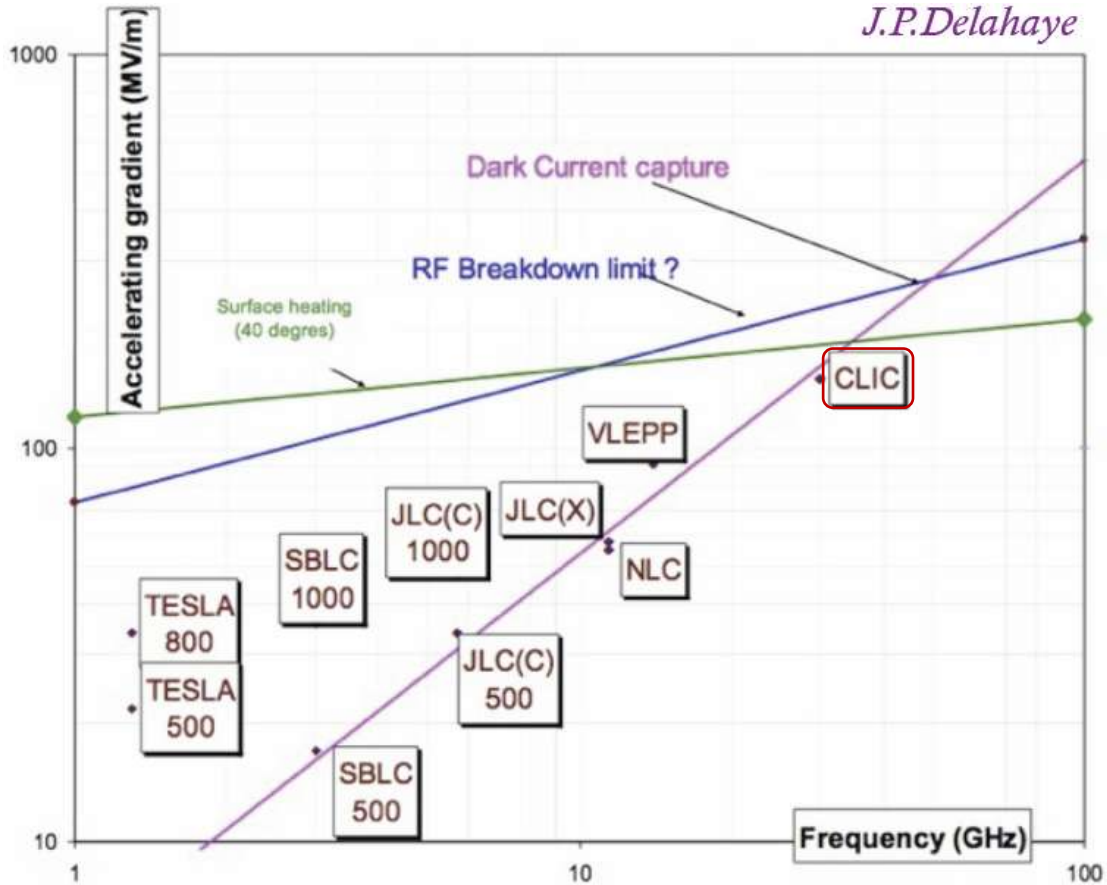
Another "Too Big of a Machine"

- VLHC or "*pipetron*"
  - ➢ 233 km , >10 B$



Option #1: UHF RF + New Materials

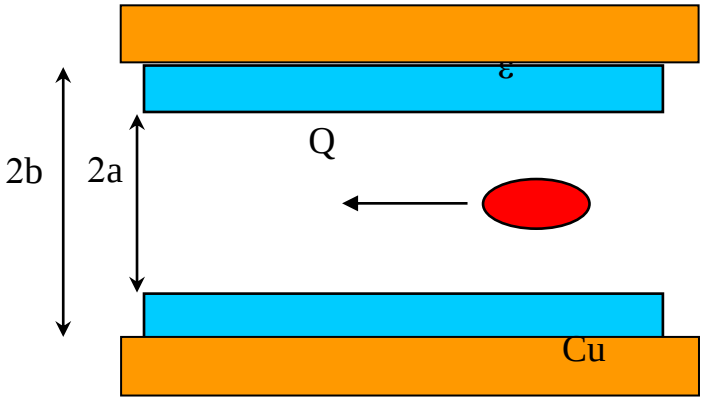
- Normal conducting cavities
  - usually, copper
  - driven by RF sources, beams



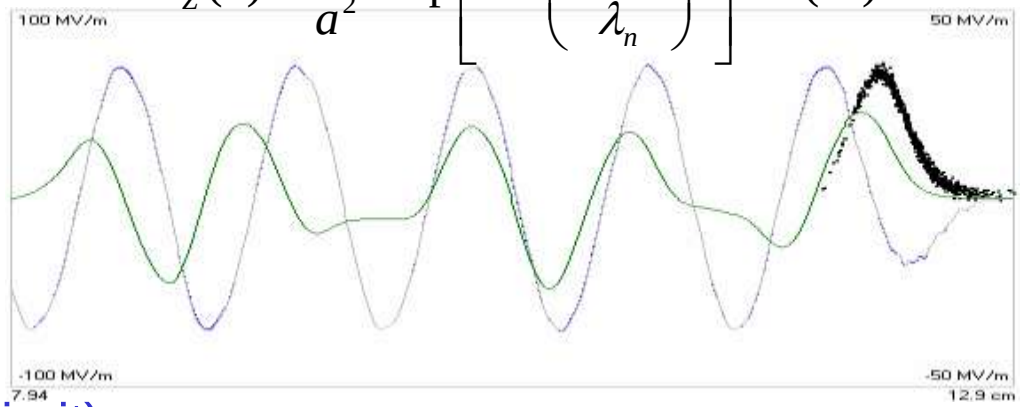
Breakdown limits metal:

$$E_s = 220(f[\mathrm{GHz}])^{1/3}\ \mathrm{MV/m}$$

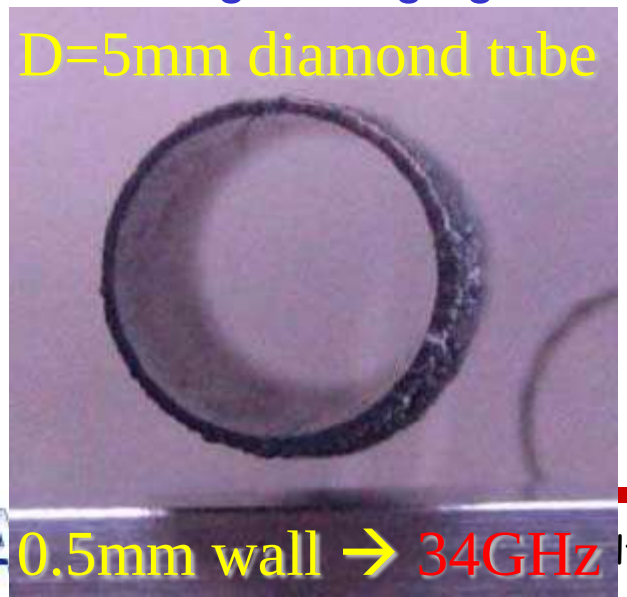
Wakefields In Dielectric Tube

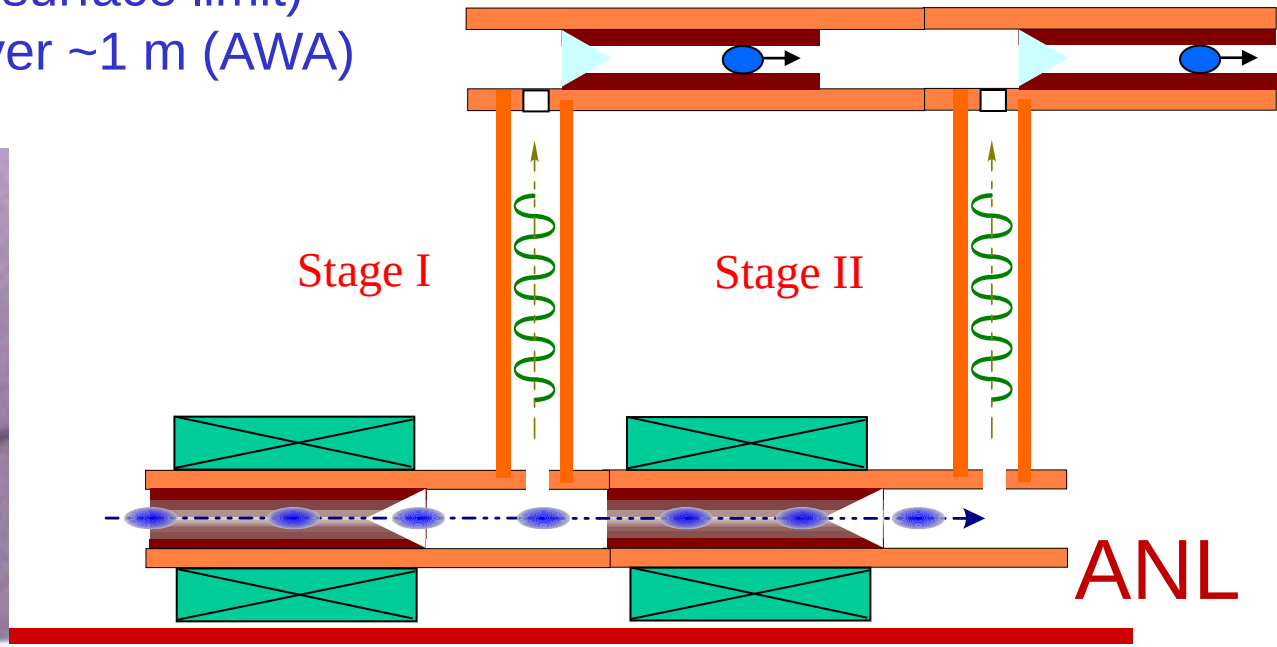


$$W_Z(z) \approx \frac{Q}{a^2} \exp\left[-2\left(\frac{\pi\,\sigma_z}{\lambda_n}\right)^2\right]\cos(kz)$$



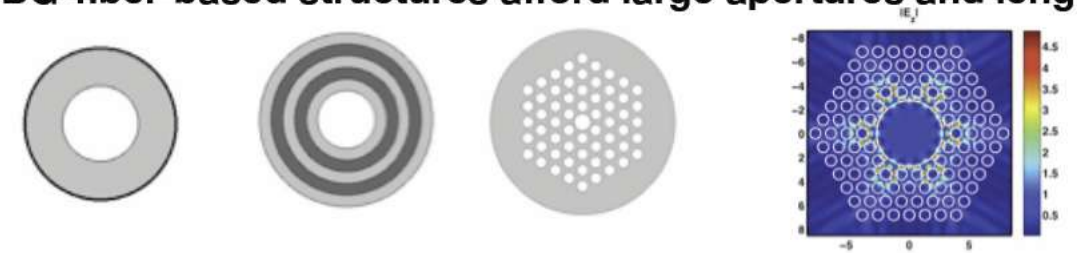
Goal ~1GV/m (diamond surface limit)
Achieved ~100 MV/m over ~1 m (AWA)
Challenge - staging





Option #2: Optical Microstructures

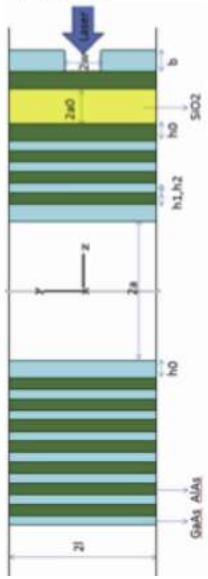
PBG-fiber-based structures afford large apertures and length-scalability



~2.5 GV/m

Planar structures offer beam dynamics advantages as well as ease of coupling power

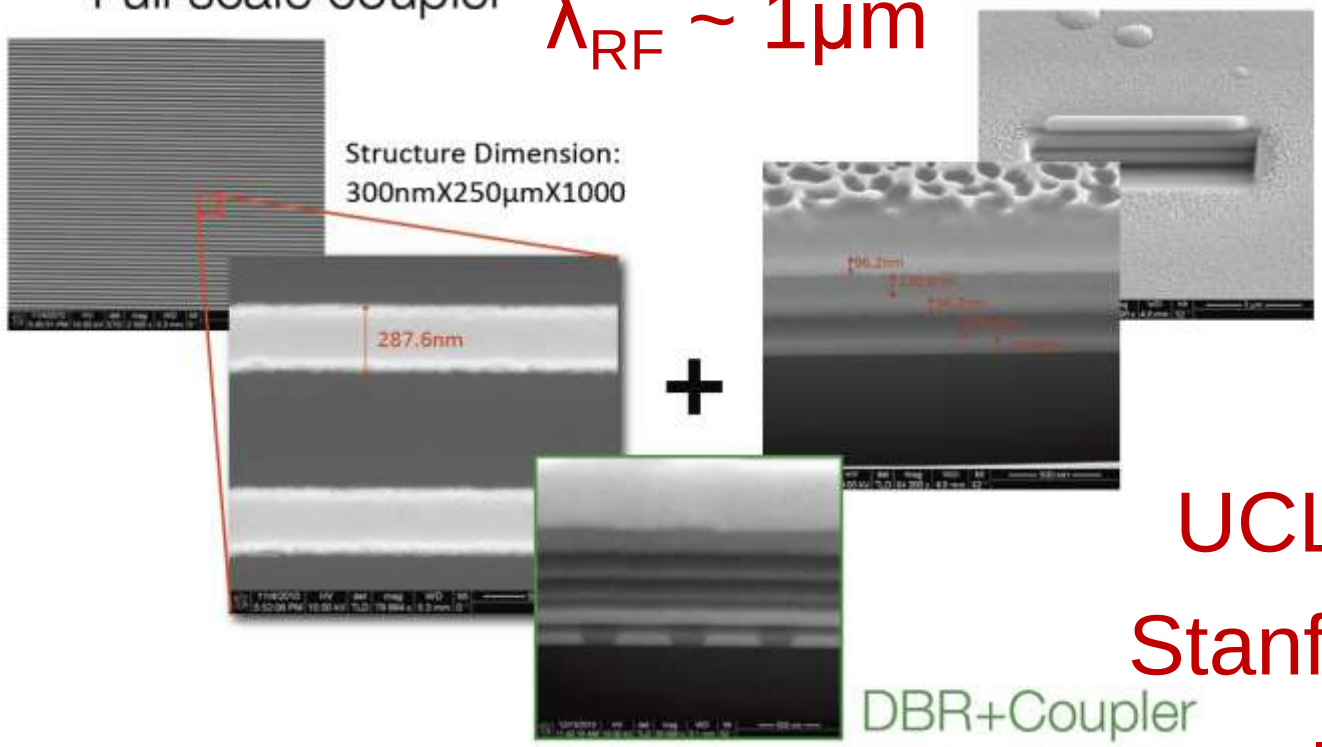
MAP



Full scale coupler

$\lambda_{RF} \sim 1\mu m$

DBR



- Micro Accelerator Platform
  - combines structure and laser
  - 1 mm 1 MeV, 1000 cav's

UCLA

Stanford

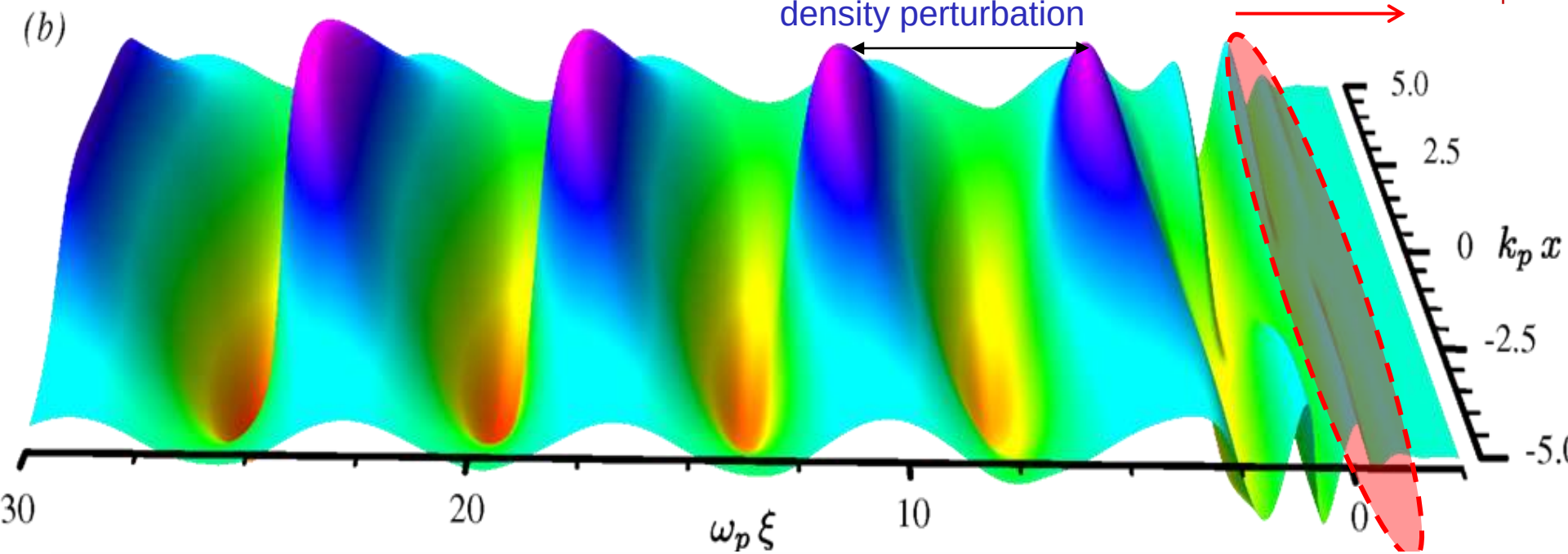
"Stawman" Dielectric Laser LC

		ILC Nom.	DLA
E_cms	GeV	1000	1000
Bunch Charge	e	2.00E+10	1.00E+04
# bunches/train	#	2820	375
train repetition rate	MHz	5.00E-06	20
final bunch length	psec	1.00	1
design wavelength	micron	230609.58	0.8
Invariant Emittances	micron	10/0.04	1e-04/1e-04
I. P. Spot Size	nm	554/3.5	0.5/0.5
Enh Lumi/ top1%	**/cm^2/s**	**4.34E+34**	**4.58E+34**
Beam Power	MW	22.6	6.0
Wall-Plug Power	MW	104.0	120.1
Gradient	MeV/m	30	830
Total Linac Length	km	33.3	1.2

Issues: 1 TeV c.m. *e*+*e*- is about max (in 10 km one can get ~8 TeV but AC power will be enormous ~GW)

Excitation of Plasma Waves

Idea- Tajima & Dawson, Phys. Rev. Lett. (1979)



$$E_0 = \frac{m_e c \omega_p}{e} \approx 100[\frac{GeV}{m}] \cdot \sqrt{n_0[10^{18} cm^{-3}]}$$

Option #3:

Short intense e-/e+/p bunch

10^{18}cm^{-3}, 100 GV/m, λ_p~30μm

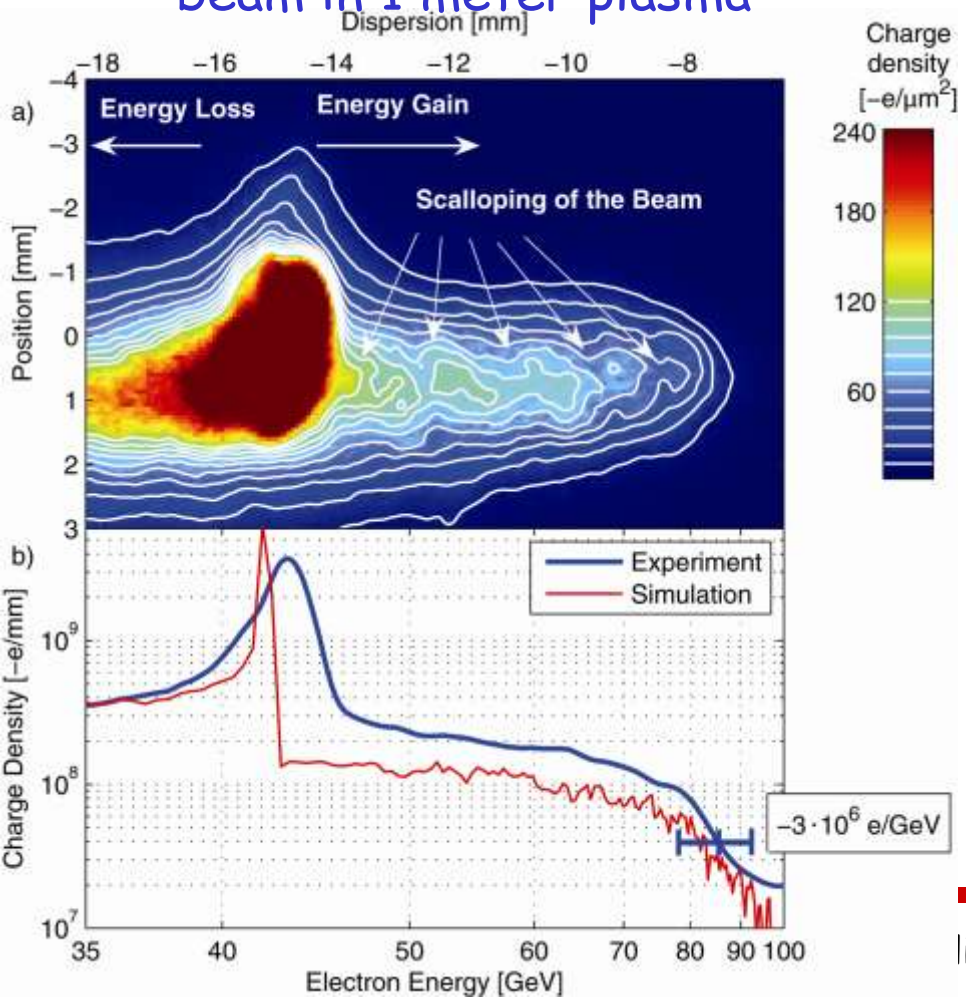
Option #4:

Short intense laser pulse

10^{17}cm^{-3}, 30 GV/m, λ_p~100μm

Option #3: Beam Excites Plasma

- Acceleration gradients of ~50 GV/m (3000 x SLAC)
  - Doubled energy of 45 GeV beam in 1 meter plasma

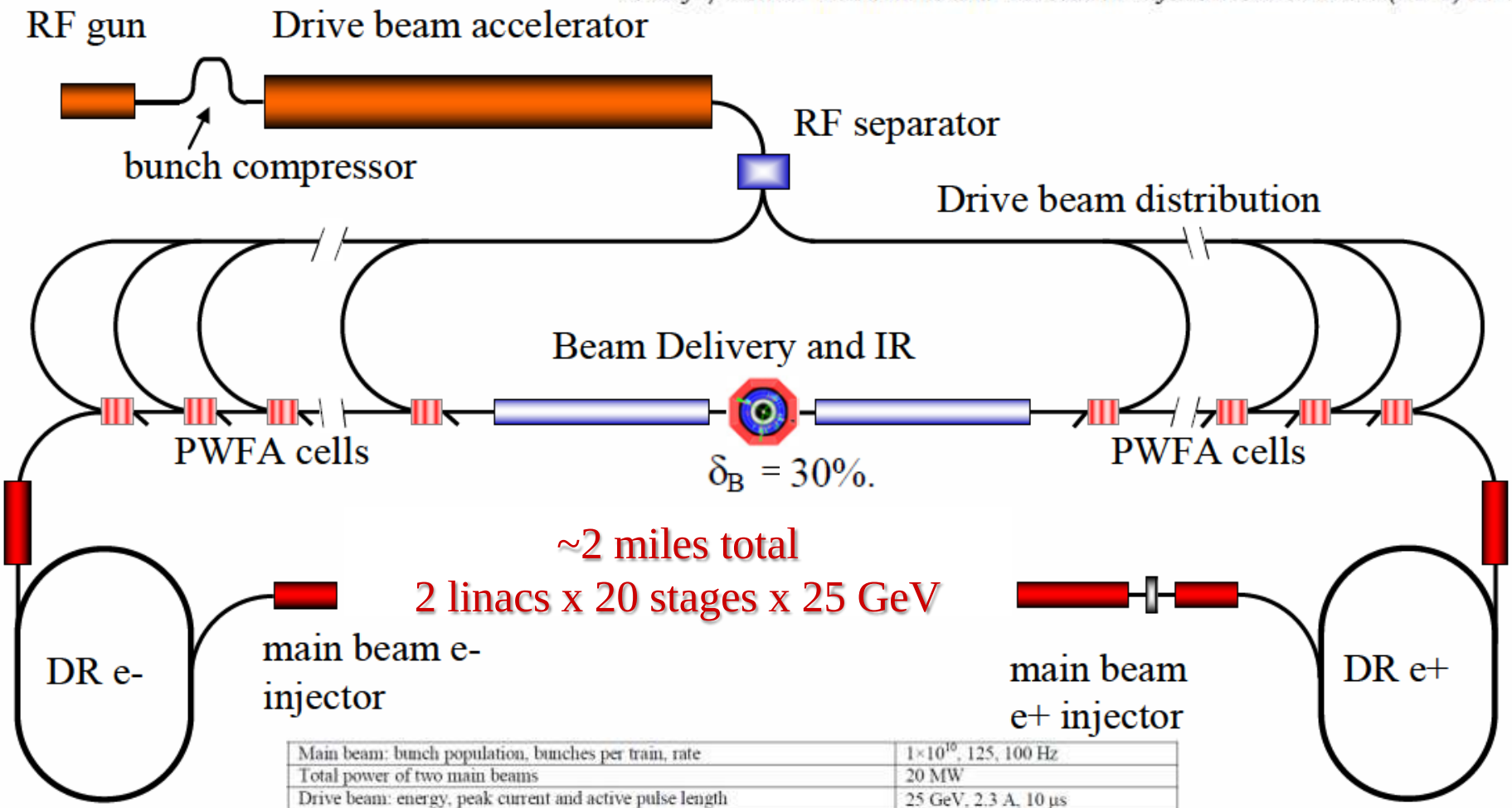


Challenges/Issues:

- small (dE/E, size) beam still to be achieved
- (FACET experiment at SLAC underway)
- needs unique drive beam
- defocuses positrons
- hard to preserve ultra small beam emittances
- thinking of using protons as a drive (at CERN)

Plasma Wake Field *e*+*e*- 1 TeV

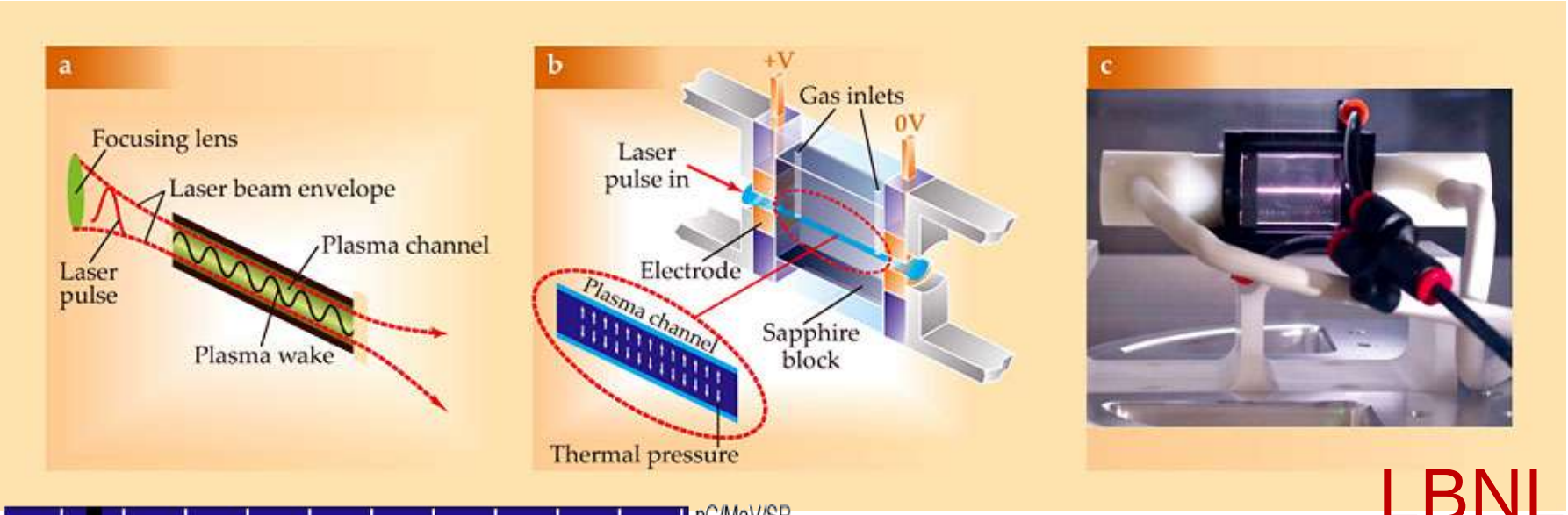
A. Seryi / Nuclear Instruments and Methods in Physics Research A 623 (2010) 23–28



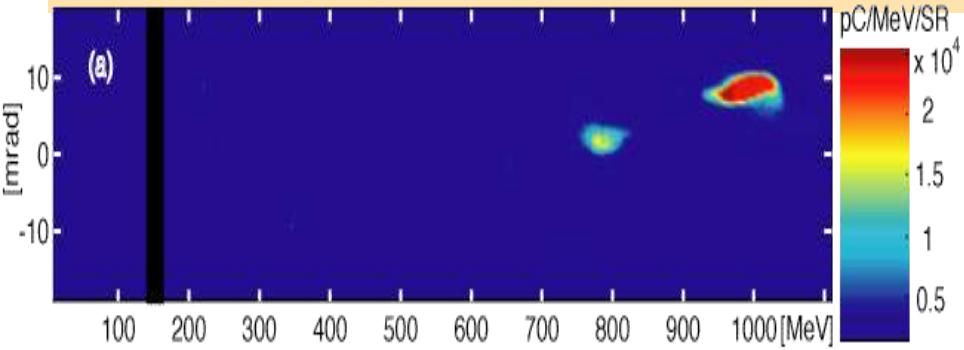
Main beam: bunch population, bunches per train, rate	1×10^{10}, 125, 100 Hz
Total power of two main beams	20 MW
Drive beam: energy, peak current and active pulse length	25 GeV, 2.3 A, 10 μs
Average power of the drive beam	58 MW
Plasma density, accelerating gradient and plasma cell length	1×10^{17}cm^{-3}, 25 GV/m, 1 m
Power transfer efficiency drive beam=>plasma =>main beam	35%
Efficiency: Wall plug=>RF=>drive beam	50% × 90% = 45%
Overall efficiency and wall plug power for acceleration	15.7%, 127 MW
Site power estimate (with 40MW for other subsystems)	170 MW
Main beam emittances, x, y	2, 0.05 mm-mrad
Main beam sizes at Interaction Point, x, y, z	0.14, 0.0032, 10 μm
Luminosity	3.5×10^{34} cm^{-2}s^{-1}
Luminosity in 1% of energy	1.3×10^{34} cm^{-2}s^{-1}

SLAC

Laser Excites Plasma



LBNL



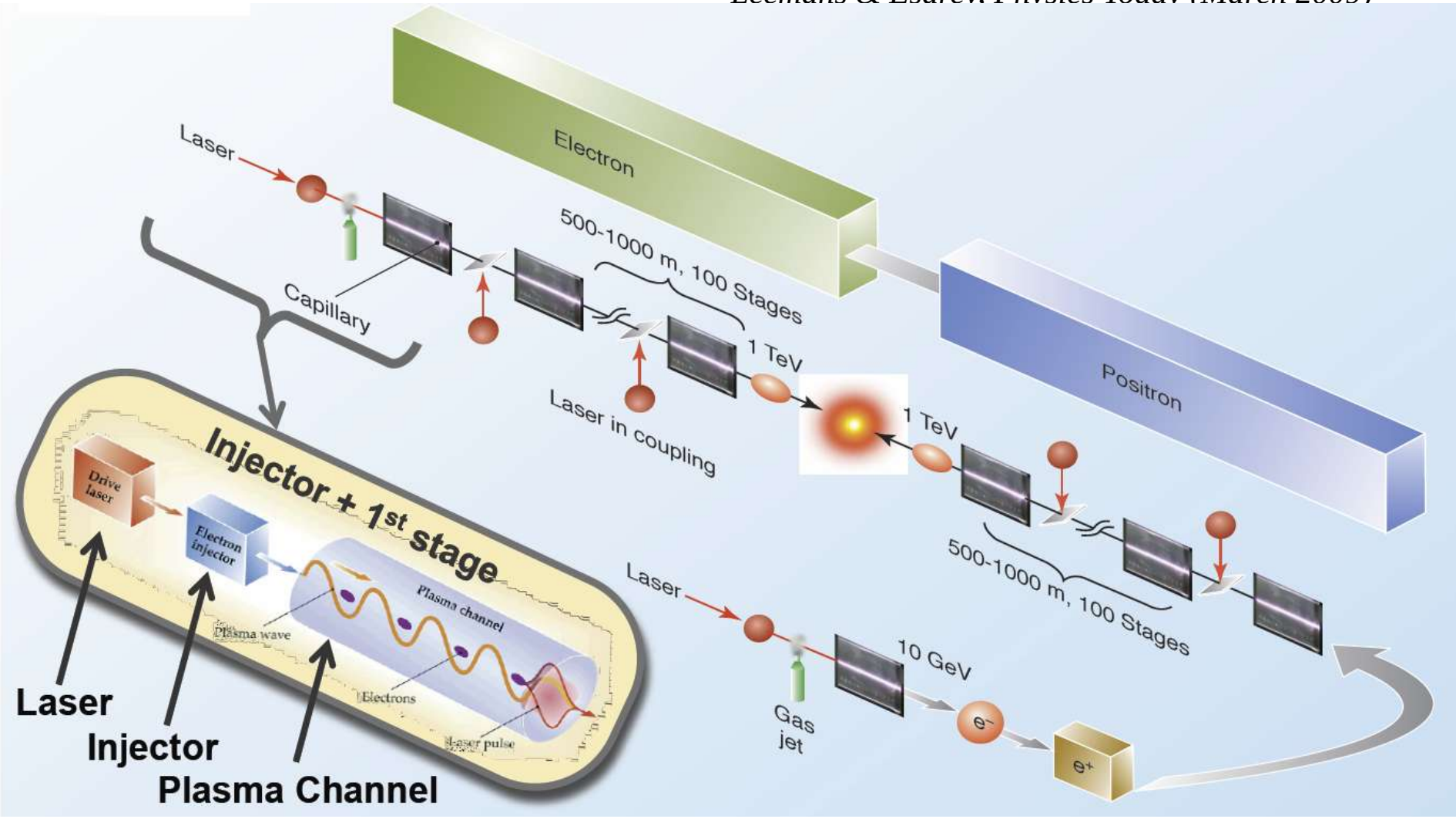
- Achieved ~30 GV/m (Berkeley)
  - 1 GeV over 3 cm with 40 TW laser
  - 2 J laser → 0.03 J beam (η=1.5%)

Challenges/Issues:

- speed of light in plasma always <c
- need many stages - hard
- BELLA experiment at LBNL with Petawatt laser (not table top!)
- low rep rate, efficiencies
- hard to preserve ultra small beams

Laser-Plasma-Accelerator LC

Leemans & Esarey, Physics Today (March 2009)

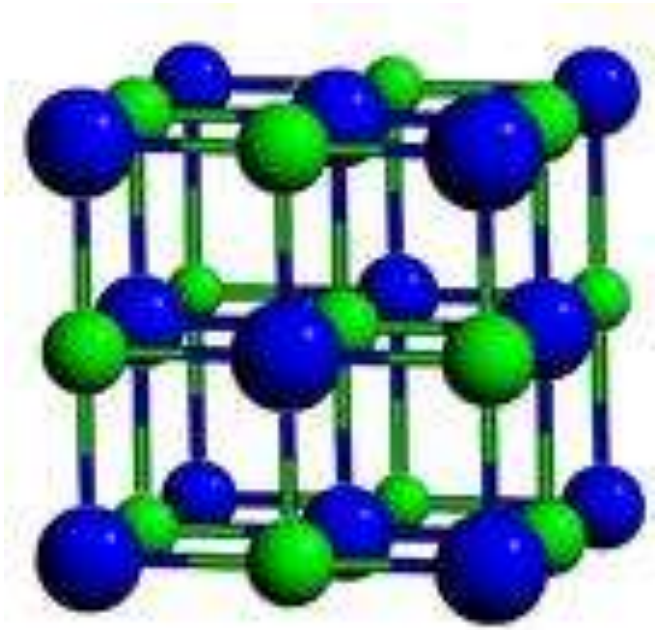


Parameter Set for LPWA LC

Case: CoM Energy (Plasma density)	1 TeV (10^{17} cm^{-3})	1 TeV (2×10^{15} cm^{-3})	10 TeV (10^{17} cm^{-3})	10 TeV (2×10^{15} cm^{-3})
Energy per beam (TeV)	0.5	0.5	5	5
Luminosity (10^{34} cm^{-2}s^{-1})	2	2	200	200
Electrons per bunch ($\times10^{10}$)	0.4	2.8	0.4	2.8
Bunch repetition rate (kHz)	15	0.3	15	0.3
Horizontal emittance $\gamma\varepsilon_x$ (nm-rad)	100	100	50	50
Vertical emittance $\gamma\varepsilon_y$ (nm-rad)	100	100	50	50
β^* (mm)	1	1	0.2	0.2
Horizontal beam size at IP σ^*_x (nm)	10	10	1	1
Vertical beam size at IP σ^*_y (nm)	10	10	1	1
Disruption parameter	0.12	5.6	1.2	56
Bunch length σ_z (μm)	1	7	1	7
Beamstrahlung parameter Υ	180	180	18,000	18,000
Beamstrahlung photons per e, n_γ	1.4	10	3.2	22
Beamstrahlung energy loss δ_E (%)	42	100	95	100
Accelerating gradient (GV/m)	10	1.4	10	1.4
Average beam power (MW)	5	0.7	50	7
Wall plug to beam efficiency (%)	6	6	10	10
One linac length (km)	0.1	0.5	1.0	5

W.Leemans, ICFA BD Newsletter, No.56 (2011)

Option #5 : Crystals

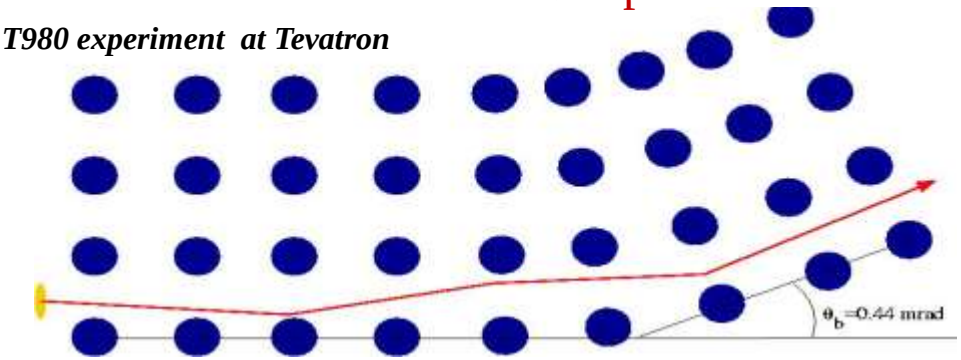


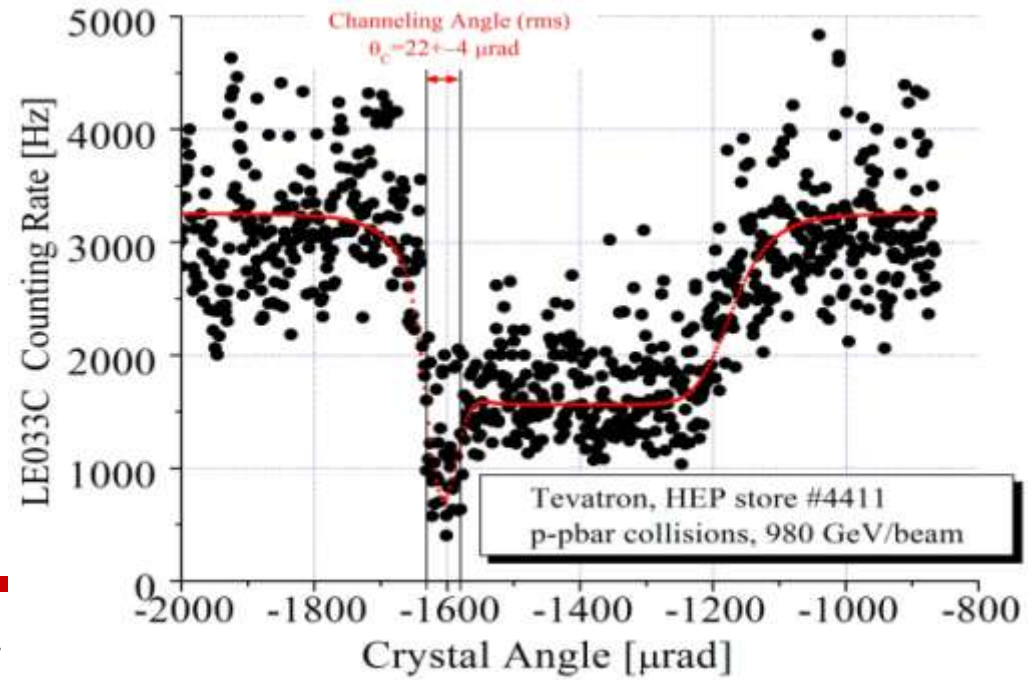
$$E_0 = \frac{m_e c \omega_p}{e} \approx 100[\frac{GeV}{m}] \cdot \sqrt{n_0[10^{18} cm^{-3}]}$$

10^{22} cm^{-3} → 10 TV/m, λ_p~ 1A

P.Chen
R.Noble
R.Ruth

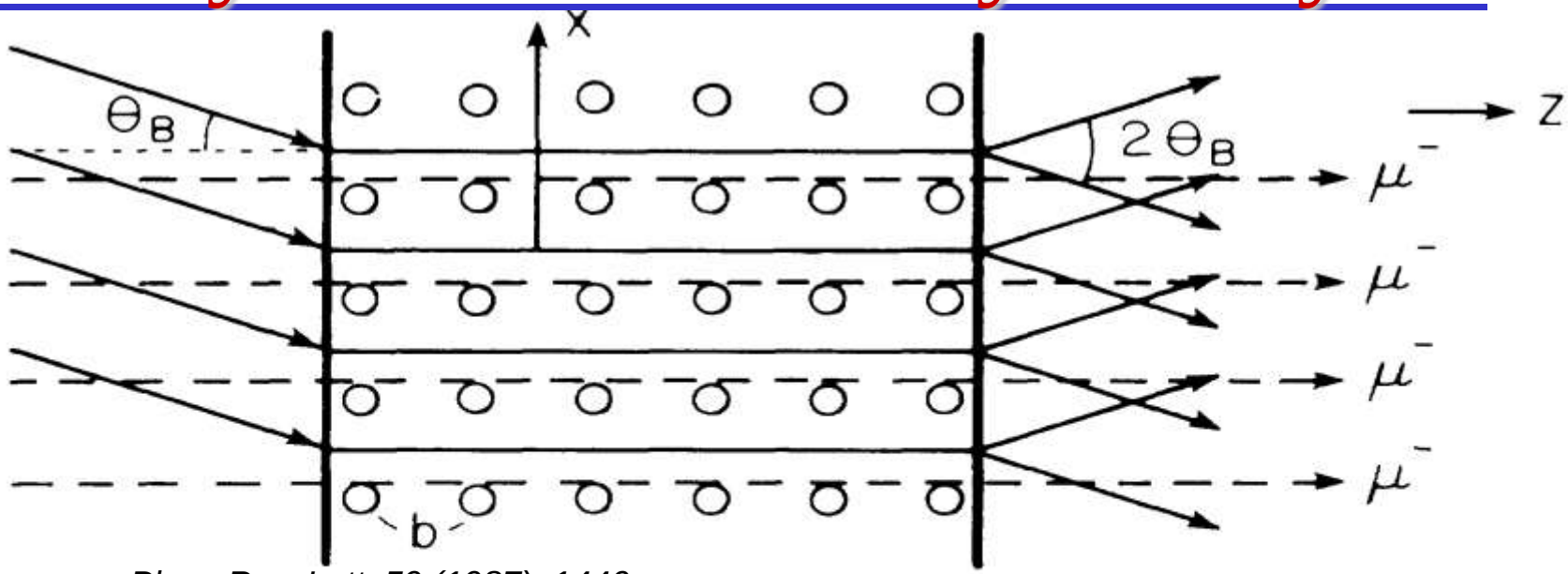
T980 experiment at Tevatron





- Strong inter-planar electric fields ~10V/A=1GV/cm
- Very stable, can be used for
  - deflection/bending (*works*)
  - focusing (*works*)
  - acceleration (*if excited*)

Crystal Excitation by X-Rays



Tajima,Cavenago, Phys. Rev. Lett. 59 (1987), 1440

FIG. 1. Bormann anomalous transmission. When the x rays are injected at the Bragg angle, the Bormann effect takes place. Particle beams are injected along the crystal axis.

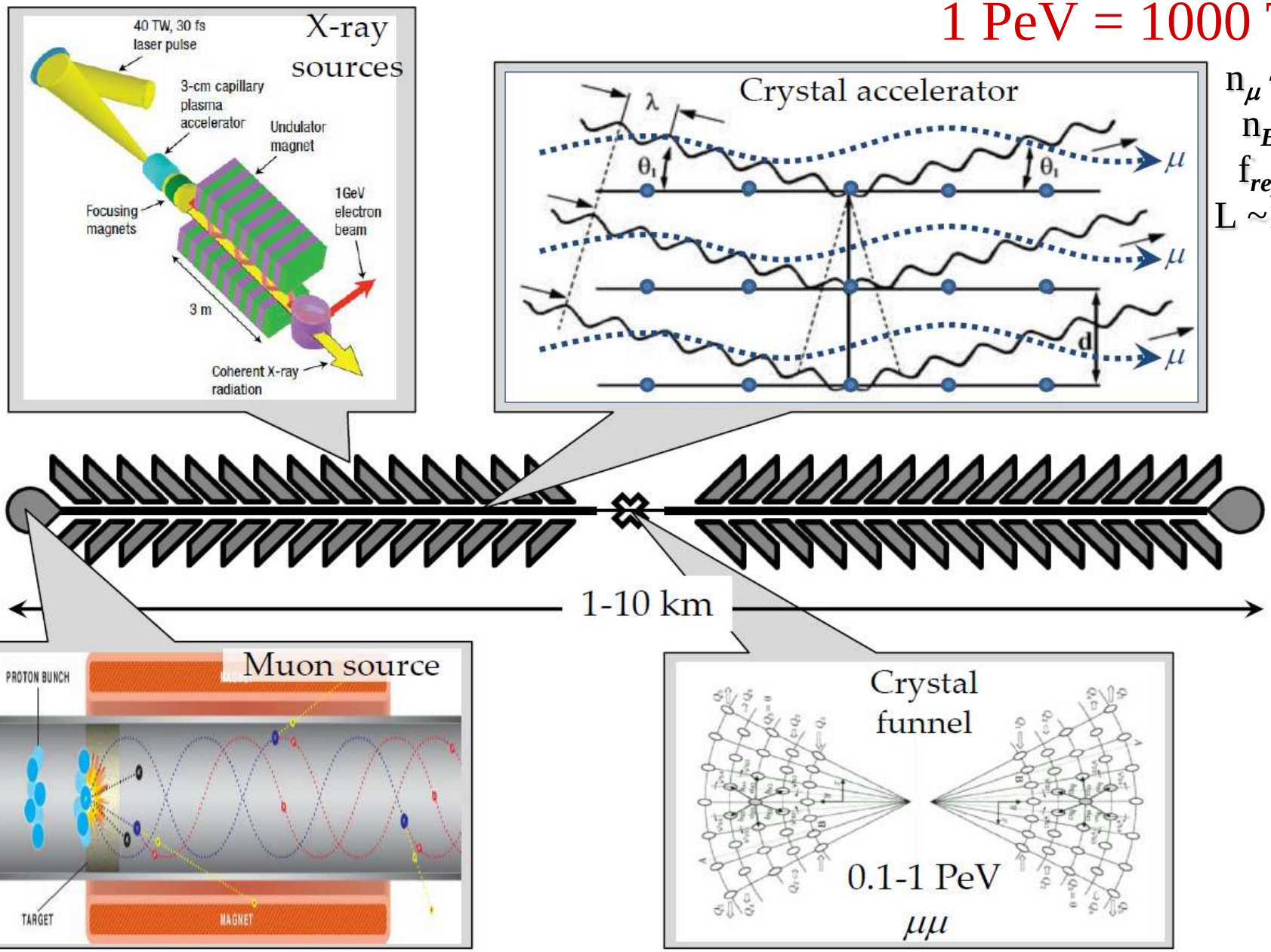
- Need 40keV high peak power x-rays
  - now available from SASE FELs like LCLS
- Gradients >1GV/cm
- Muons preferred
  - No bremstrahlung, no nucl.
- μ+ rad length 10^9 cm
  - total energy~10^9 GeV

Linear $\mu+\mu-$ Crystal X-ray Collider

V.Shiltsev, Fermilab-Pub-2012-100 (2012)

1 PeV = 1000 TeV

n_μ ~1000
n_B ~100
f_{rep} ~10^6
L ~$10^{30\text{-}32}$



Comparison of Future Options

	Dielectric based	Plasma based	Crystal channeling
Accelerating media	micro-structures	ionized plasma	solid crystals
Energy source: option 1 option 2	optical laser e^- bunch	e^- bunch optical laser	x-ray laser
Preferred particles	any stable	e^-, μ^-	μ^+, p^+
Max accelerating gradient	1-3 GV/m	30-100 GV/m	0.1-10 TV/m
c.m. energy reach in 10 km	3-10 TeV	3-50 TeV	10^3-10^5 TeV
# stages/10 km: option 1 option 2	10^5-10^6 10^4-10^5	~100 10^3-10^4	~1

Comments on Crystals

- Ultimate focusing in 1 Angstrom
- No staging – acceleration in continuous channel
  - if bending radius > 2 [m] x E [TeV]
- Energy limited by synchrotron radiation losses and scattering while channeling
  - 300 GeV for electrons
  - 1000 PeV for protons – not point-like particles
  - 10 PeV for μ + point-like particles + no beamstrahlung
- At gradients 0.1-1 TeV/m – reusable fibers
  - at > 1 TeV/m – disposable crystals

Crystals : Directions for R&D

- Muon production
  - synergy with MAP
  - can be done at ASTA
- X-ray generation
  - synergy with LPWA R&D
  - Can be done at ASTA
- Acceleration in crystals
  - can be done at LCLS or ASTA
- "Crystal funnel"
  - can be done with protons, e.g., at MTest
  - with muons – at ASTA

New Paradigm for Collider Physics

$$E_{cm}$$

Size is limited <10 km → calls for the highest gradients → crystals → muons

$$L = f\frac{N_1 N_2}{A}$$

Luminosity calls for more particles in the smallest beam size

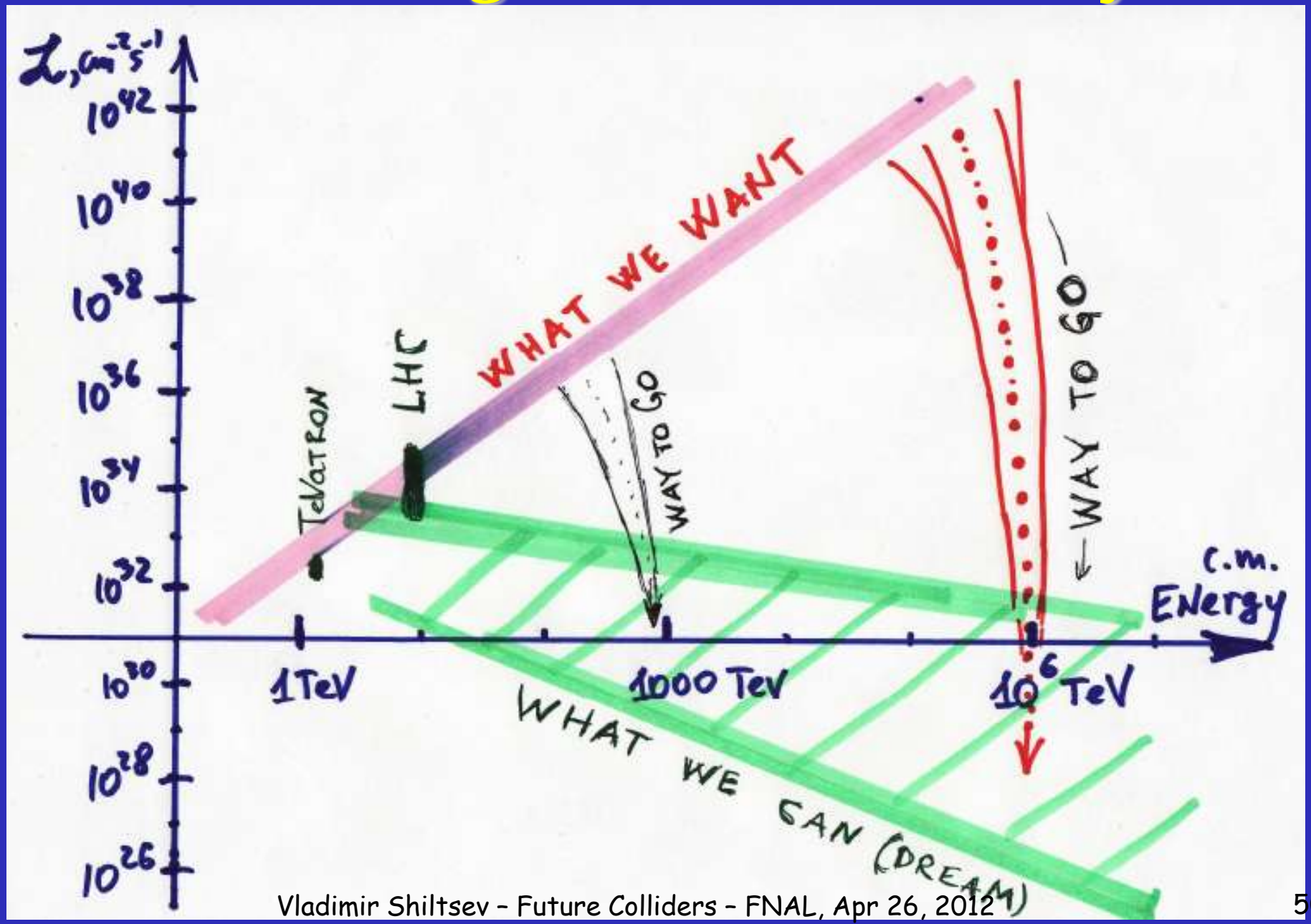
$$A \sim 1\ \text{Å}^2 = 10^{-16}\,\text{cm}^{-2}$$

This is the smallest beam size

$$P = f n_{ch} \cdot NE$$

The power is limited <10MW → *N* is small at high *E* → *L*

New Paradigm for Collider Physics



Summary

- Colliders=success: 29 built over 50 yrs, ~10 TeV c.m. achieved
- The progress has greatly slowed down due to increasing size, complexity and cost of the facilities. The prospects for the next 20 years depend on the LHC discoveries.
- Realities set constrains on the far-future colliders : **<10B$, <10 km, <10MW.**
- There are conceivable possibilities to reach 100-1000 TeV c.m. within the limits.
- At least three paradigm shifts needed:
  - development of the new technology based on ultrahigh acceleration gradients ~0.1-10 TeV/m in crystals;
  - acceleration of heavier particles, preferably, muons;
  - new approaches to physics research with luminosity limited to ~10^{30-32} $cm^{-2}s^{-1}$.
- Fermilab is well suited to carry out and lead the needed R&D