Future Accelerators

Marc Ross, SLAC - ILC

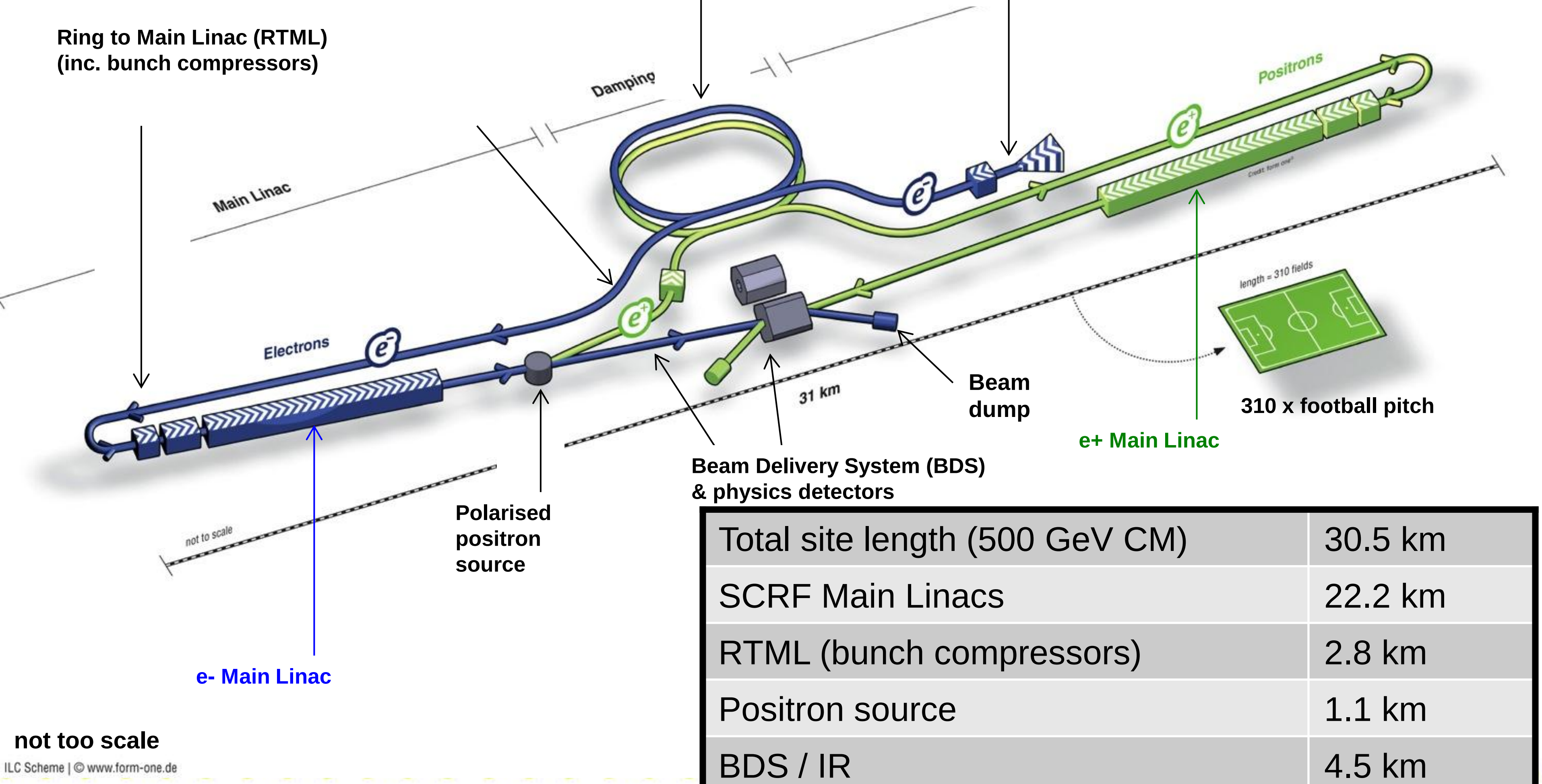
Higg's factories and beyond:

ILC and alternate schemes

Outline

- **International Linear Collider (ILC)**
  - Parameters
  - Superconducting RF and Nano-beams
  - Staging: 250 GeV to 1 TeV
- **e+/e- Ring Colliders**
  - Parameters
  - AC Power Consumption and Construction Cost
  - Tunneling near CERN
- **μ+/μ- Colliders**
  - Staging and Parameters
  - R & D

ILC in a Nutshell



Damping Rings

Polarised electron source

Ring to Main Linac (RTML)
(inc. bunch compressors)

Beam dump

310 x football pitch

e+ Main Linac

Beam Delivery System (BDS)
& physics detectors

Polarised positron source

e- Main Linac

not too scale

Total site length (500 GeV CM)	30.5 km
SCRF Main Linacs	22.2 km
RTML (bunch compressors)	2.8 km
Positron source	1.1 km
BDS / IR	4.5 km
Damping Rings (circumference)	3.2 km

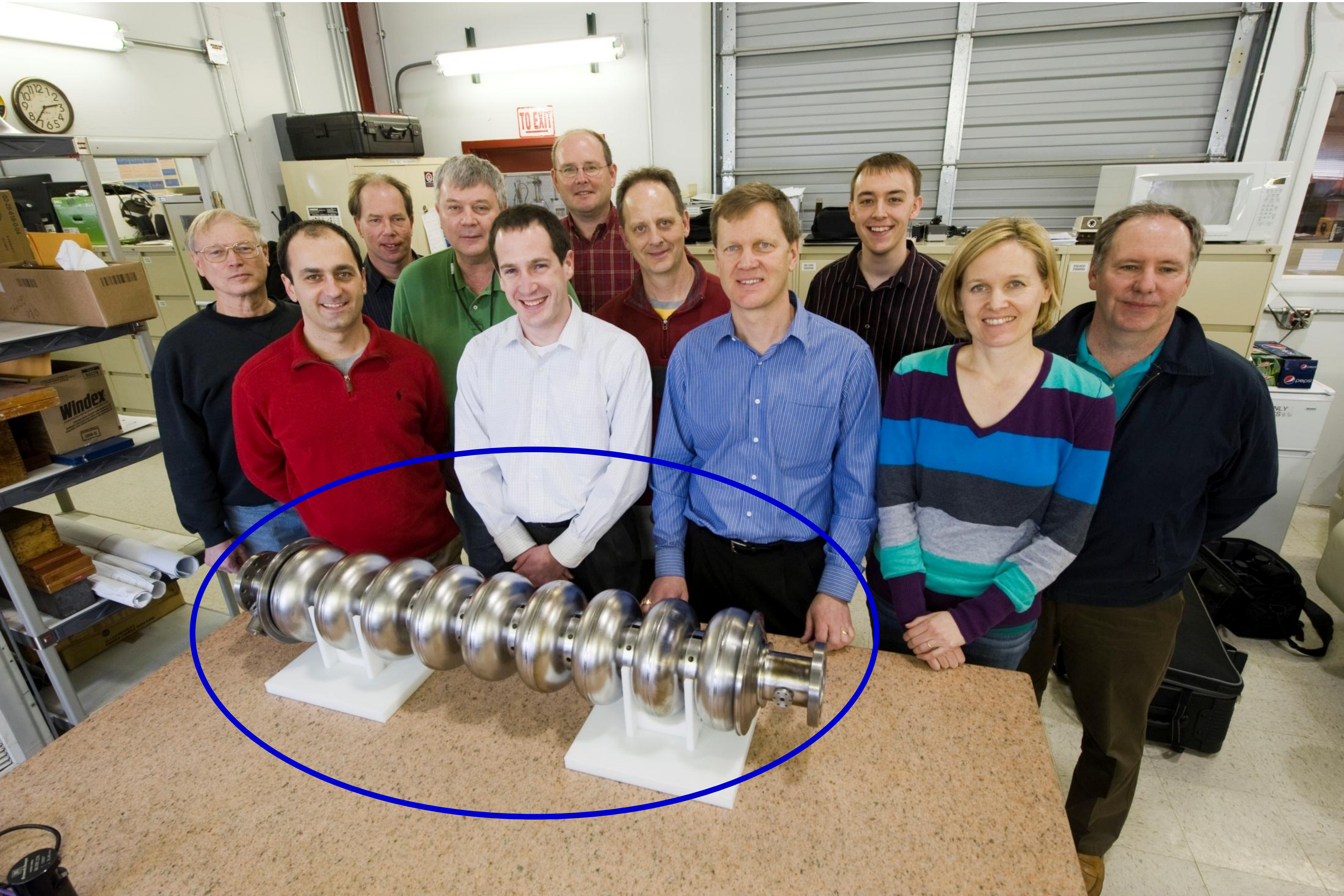
ILC Parameters

			Baseline	1st Stage	L Upgrade	TeV Upgrade	
						A	B
Centre-of-mass energy	E_{CM}	GeV	500	250	500	1000	1000
Collision rate	f_{rep}	Hz	5	5	5	4	4
Electron linac rate	f_{linac}	Hz	5	10	5	4	4
Number of bunches	n_b		1312	1312	2625	2450	2450
Bunch population	N	$\times 10^{10}$	2.0	2.0	2.0	1.74	1.74
Bunch separation	Δt_b	ns	554	554	366	366	366
Pulse current	I_{beam}	mA	5.79	5.8	8.75	7.6	7.6
Average total beam power	P_{beam}	MW	10.5	5.2	21.0	27.2	27.2
Estimated AC power	P_{AC}	MW	162	128	205	300	300
RMS bunch length	σ_z	mm	0.3	0.3	0.3	0.250	0.225
Electron RMS energy spread	$\Delta p/p$	%	0.124	0.190	0.124	0.083	0.085
Positron RMS energy spread	$\Delta p/p$	%	0.070	0.152	0.070	0.043	0.047
Electron polarisation	P_-	%	80	80	80	80	80
Positron polarisation	P_+	%	30	30	30	20	20
Horizontal emittance	$\gamma\epsilon_x$	µm	10	10	10	10	10
Vertical emittance	$\gamma\epsilon_y$	nm	35	35	35	30	30
IP horizontal beta function	β_x^*	mm	11.0	13.0	11.0	22.6	11.0
IP vertical beta function (no TF)	β_y^*	mm	0.48	0.41	0.48	0.25	0.23
IP RMS horizontal beam size	σ_x^*	nm	474	729	474	481	335
IP RMS veritcal beam size (no TF)	σ_y^*	nm	5.9	7.7	5.9	2.8	2.7
Luminosity (inc. waist shift)	L	$\times 10^{34}$ cm^{-2}s^{-1}	1.8	0.75	3.6	3.6	4.9
Fraction of luminosity in top 1%	$L_{0.01}/L$		58.3%	87.1%	58.3%	59.2%	44.5%
Average energy loss	δ_{BS}		4.5%	0.97%	4.5%	5.6%	10.5%
Number of pairs per bunch crossing	N_{pairs}	$\times 10^3$	139.0	62.4	139.0	200.5	382.6
Total pair energy per bunch crossing	E_{pairs}	TeV	344.1	46.5	344.1	1338.0	3441.0

ILC Overview

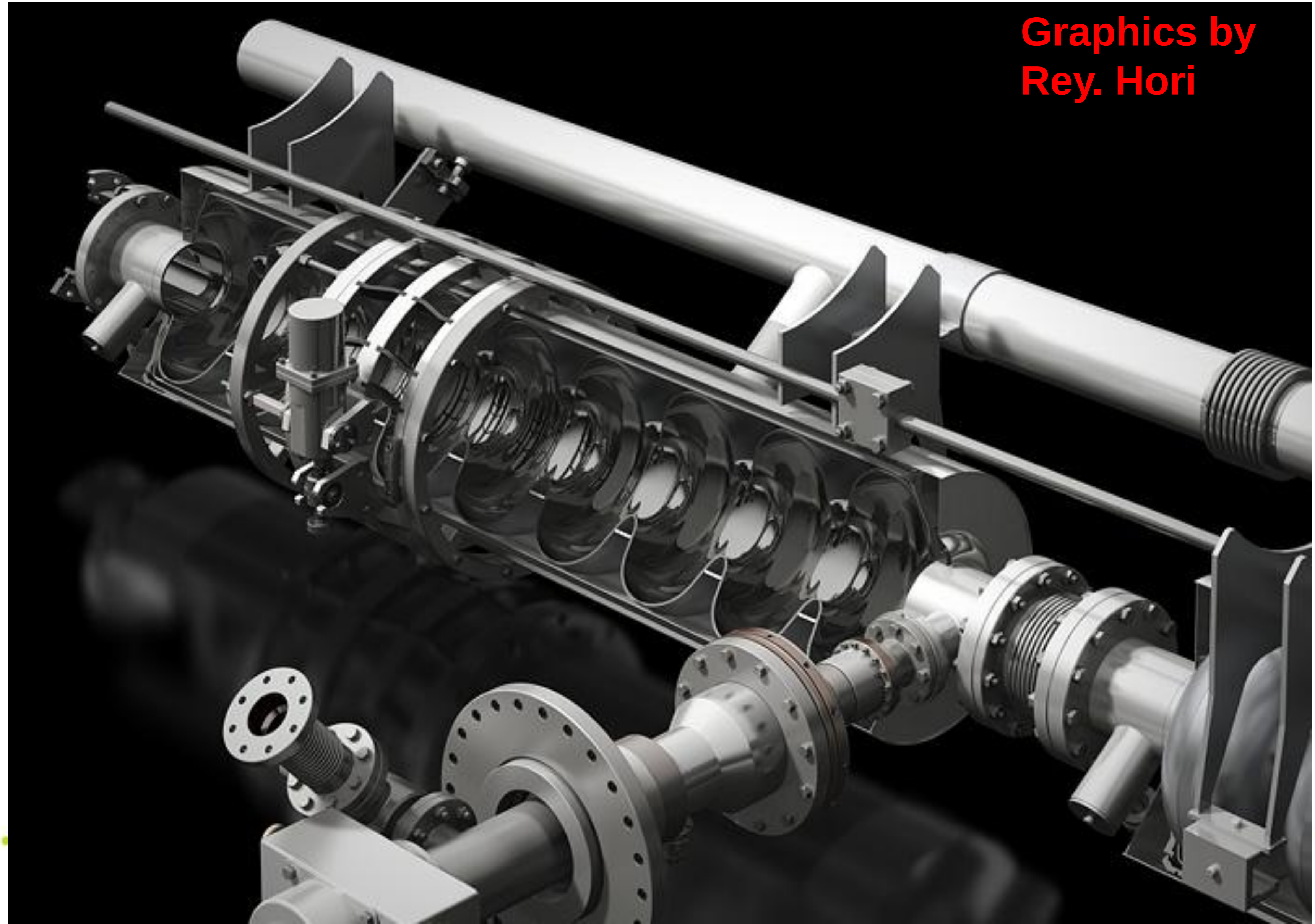
- **Designed *and optimized* for 500 GeV E_{cm}; upgradeable to 1 TeV**
- **L_{500} ~ 1.8e34 with 162 MW wall plug**
  - L_{1000} ~ 5e34 with 300 MW wall plug
- **R & D program completed: Detailed Design**
  - Technology Demonstrated (**SCRF**)→
  - 8%-scale Demonstration '**E-XFEL**' (DESY) in 2015
  - IR optics & tuning Demonstration '**ATF-II**' (KEK) →
- **Physics Studies, Detector / Machine Design Report *completed 02.2013***
  - Culmination of 6 year design study

Fermilab – Niowave SCRF Cavity Team



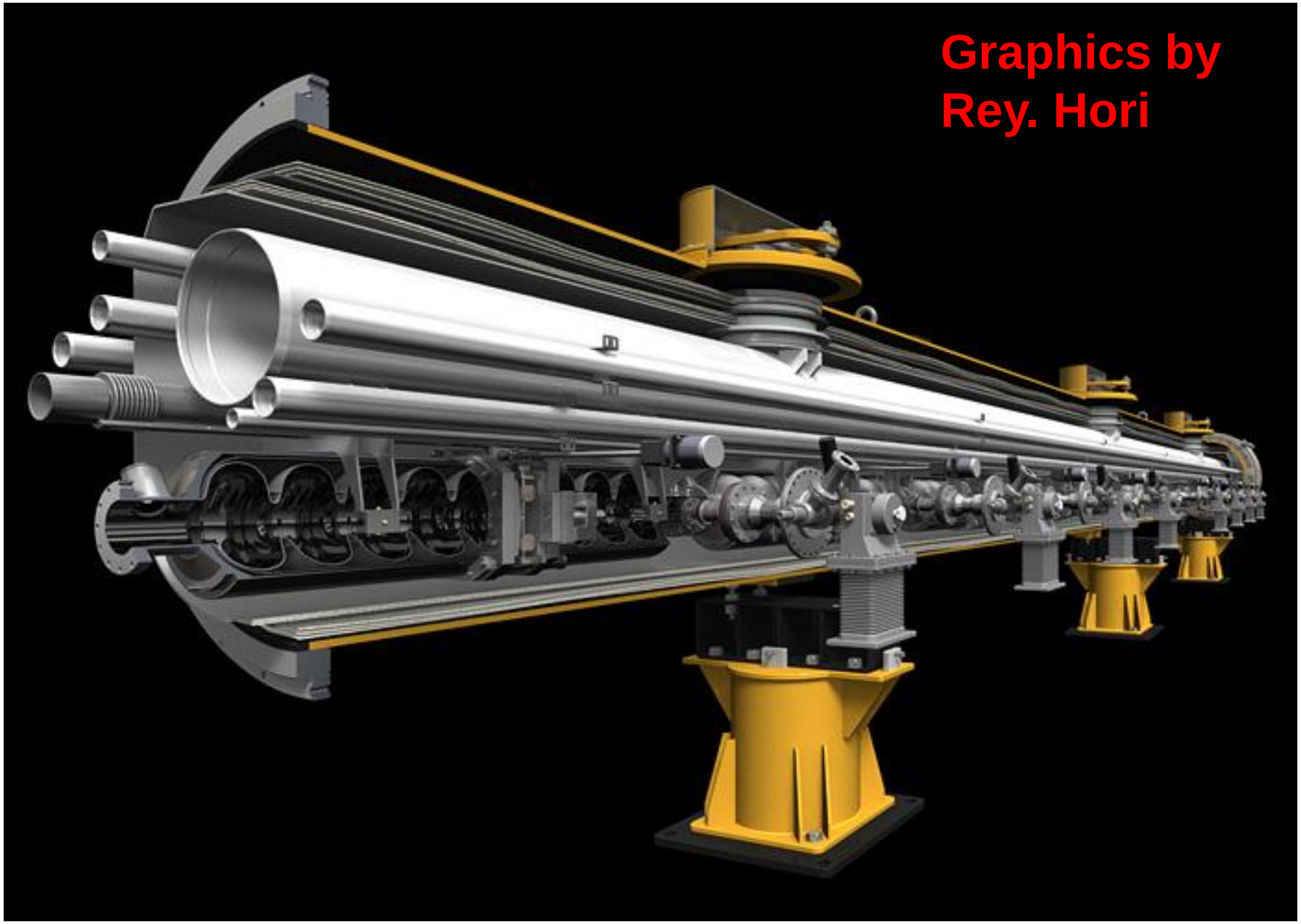
ILC Cavity Assembly

(Helium tank, mag. shield, tuner and coupler)



Graphics by
Rey. Hori

Linac building block: the Cryomodule:

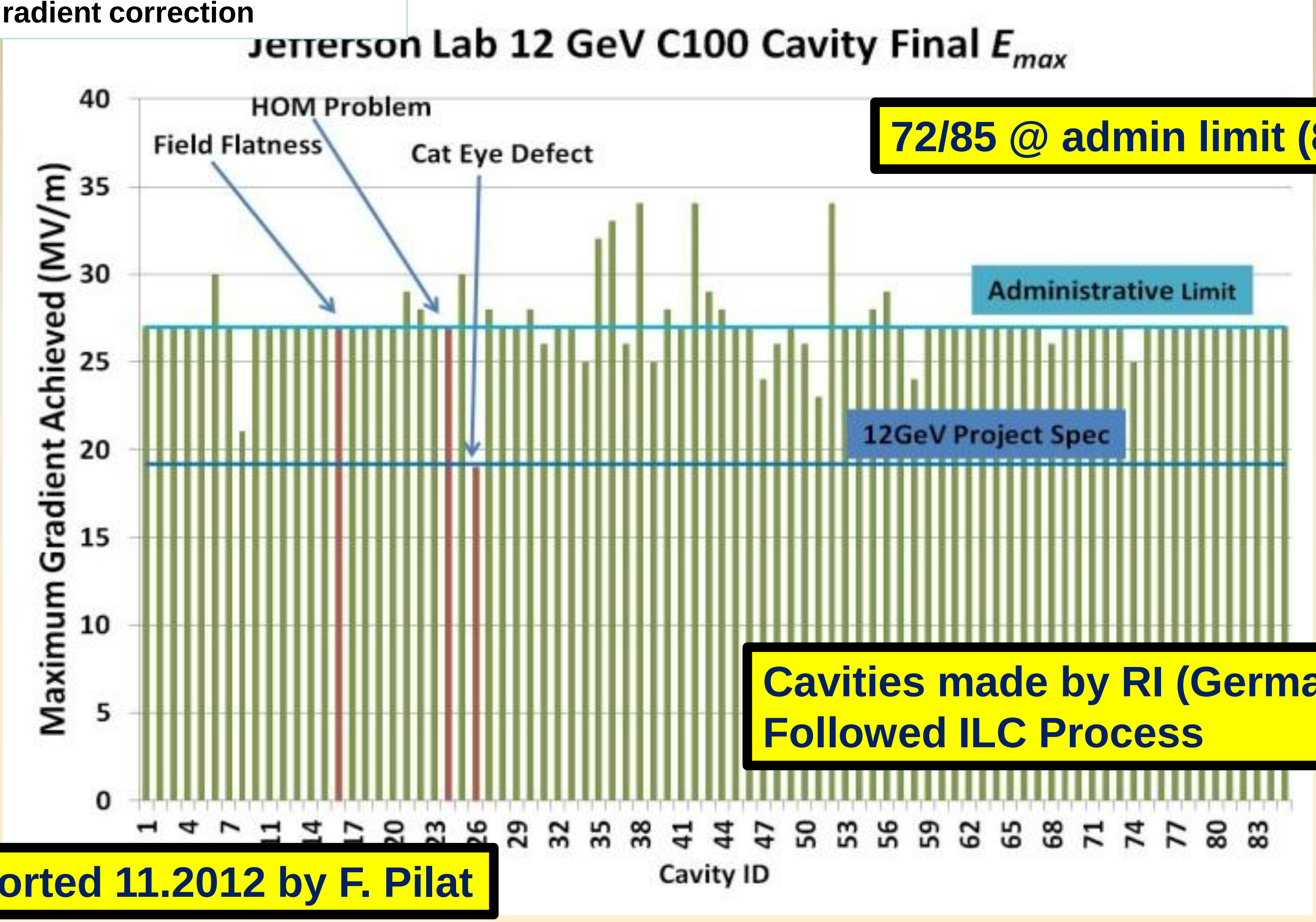


Graphics by
Rey. Hori

CEBAF 12 GeV upgrade

12 GeV cavities: overall performance

**Vertical Test; 1500 MHz 7 cell;
10% gradient correction**

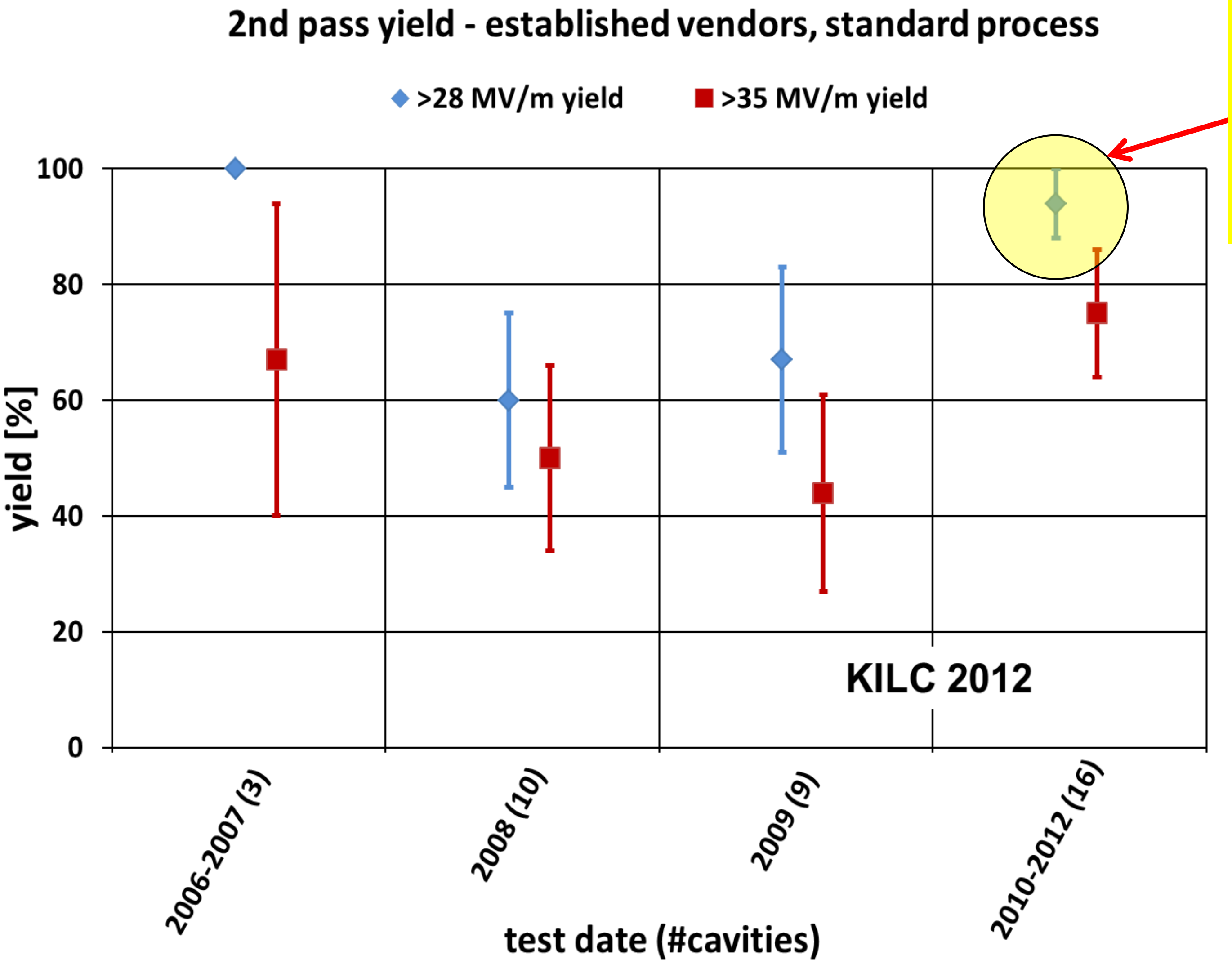


72/85 @ admin limit (85%)

**Cavities made by RI (Germany);
Followed ILC Process**

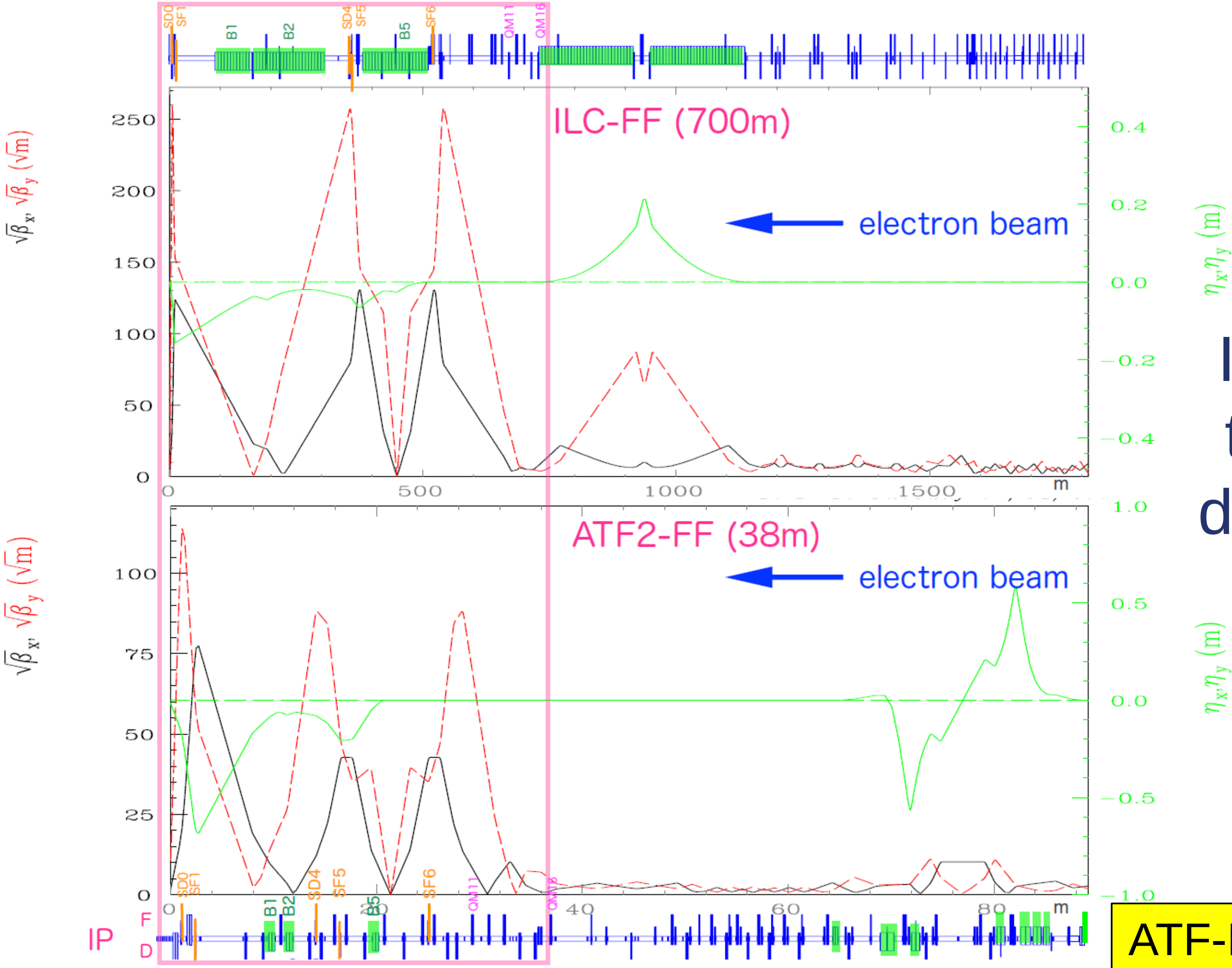
Reported 11.2012 by F. Pilat

Global Progress in ILC Cavity Gradient Yield



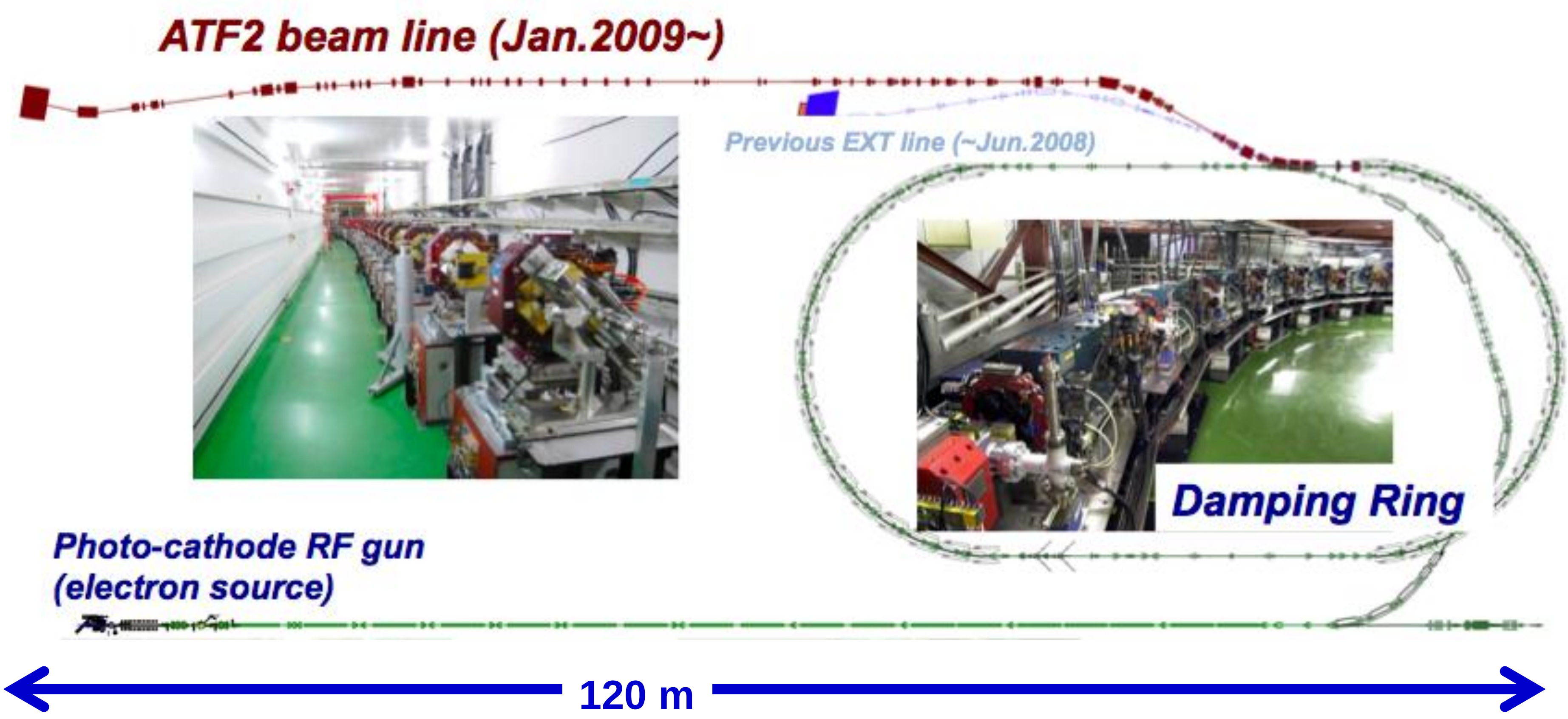
(94+/-6)% acceptable for ILC mass production

IT optics and tuning beam demonstration



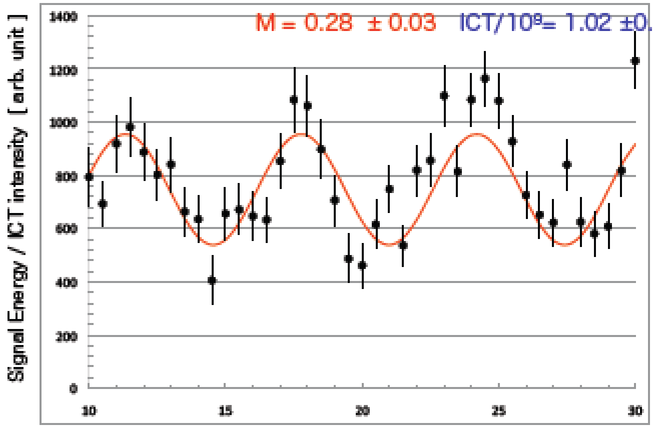
ATF-II at KEK
Model Final-Focus optics system
Beam from ultra-low emittance damping ring

KEK - ATF2 Facility Layout



ATF-2 achieves 72.8 nm

Preliminary ATF2@KEK meas121221_183019



M = 0.28 ± 0.03 ICT/10^9= 1.02 ±0.11(rms)

Phase [rad] at 174 degree mode
266nm/pitch

2012

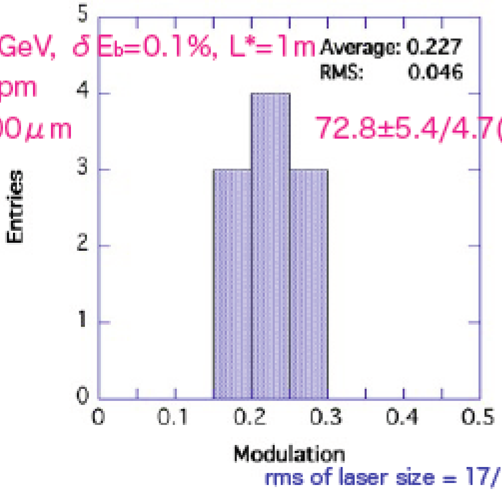
Preliminary

Modulation for 174deg Mode
2012/12/21

E_b=1.3GeV, δE_b=0.1%, L^*=1m
ε_y=20pm
β^*_y=100μm

Average: 0.227
RMS: 0.046

72.8±5.4/4.7(rms)nm



rms of laser size = 17/12um

FFTB@SLAC

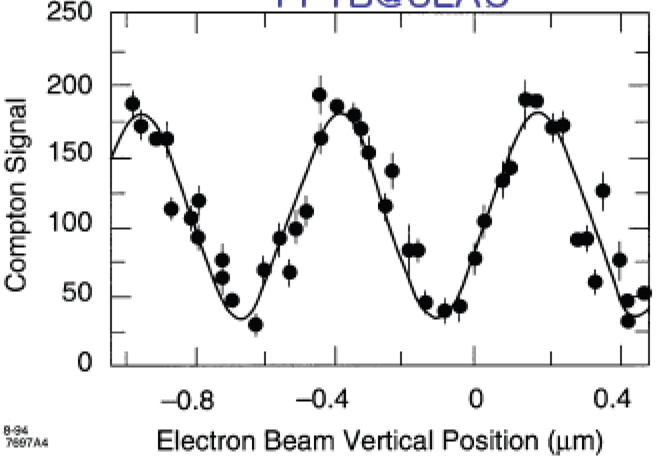


Figure 5.6: Laser-Compton beam size measurement performed in May of 1994. The measured size is 77±7 nanometers.

1994

Both assumes no modulation reduction

E_b=46.6GeV, δE_b=0.05%, L^*=0.4m
ε_y=20pm
β^*_y=100μm

77±7(rms)nm

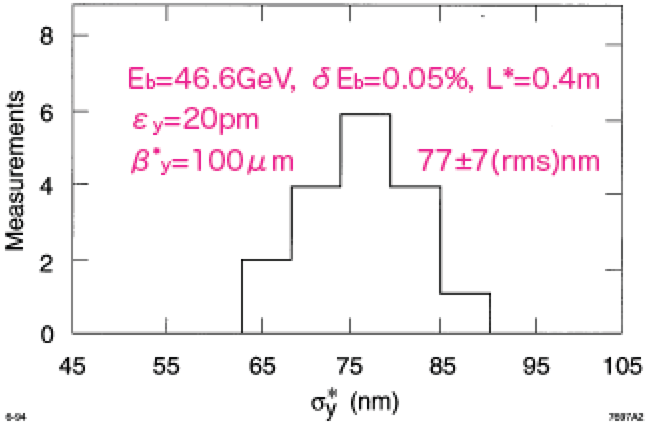


Figure 5.7: Histogram of measurements made during the last 3 hours of the May, 1994 FFTB run. Average size measured was 77 nm, with an RMS of 7 nm.

rms of laser size = 50um -> M reduction of 10%

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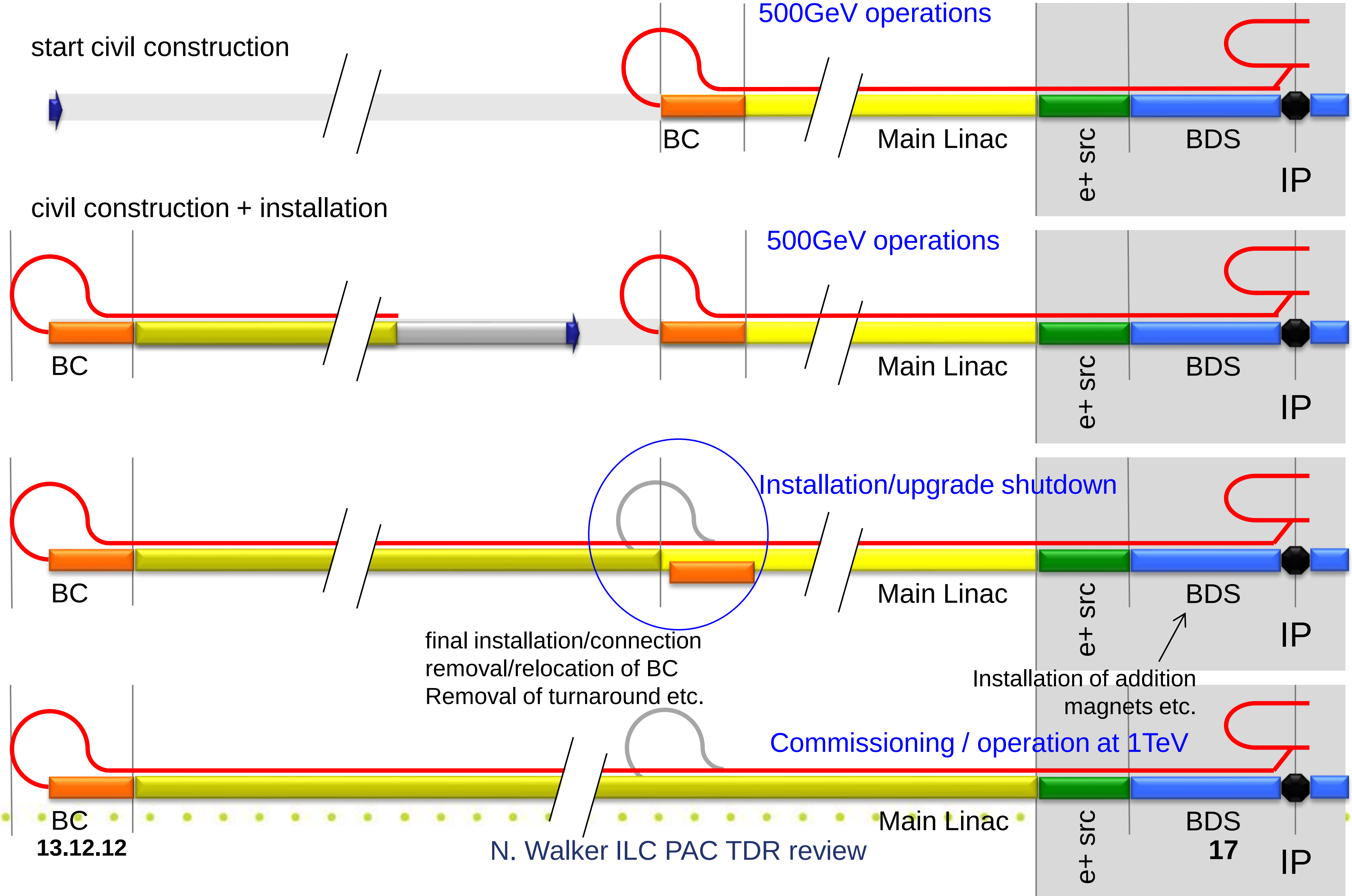
Luminosity Upgrade

- Concept: increase n_b from 1312 → 2625
  - **Reduce linac bunch spacing 554 ns → 336 ns**
  - **Increase pulse current 5.8 → 8.8 mA**
  - **Increase number of klystrons by ~50%**
- Doubles beam power → ×2 L ($3.6\times10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$)
- Damping ring:
  - **Electron ring doubles current (389mA → 778mA)**
  - **Positron ring: possible 2nd (stacked) ring (e-cloud limit)**
- AC power: 161 MW → 204 MW (est.)
  - **AC power increased by ×1.5**
  - **shorter fill time and longer beam pulse results in higher RF-beam efficiency (44% → 61%)**

TeV upgrade: Construction Scenario



start civil construction

500GeV operations

BC

Main Linac

e+ src

BDS

IP

civil construction + installation

500GeV operations

BC

Main Linac

e+ src

BDS

IP

Installation/upgrade shutdown

BC

Main Linac

e+ src

BDS

IP

final installation/connection
removal/relocation of BC
Removal of turnaround etc.

Installation of addition magnets etc.

Commissioning / operation at 1TeV

BC

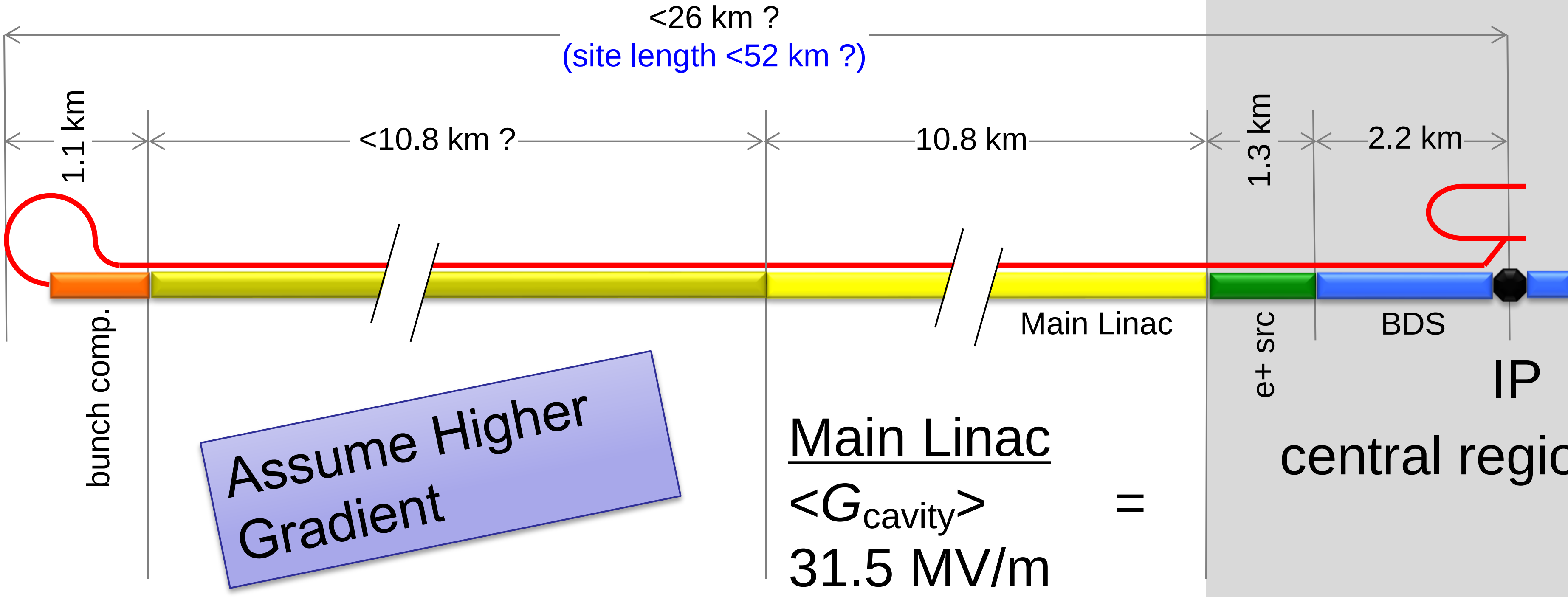
Main Linac

e+ src

BDS

IP

TeV Upgrade

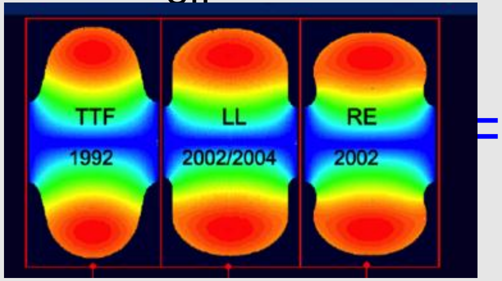


Assume Higher Gradient

Main Linac

$\langle G_{cavity} \rangle$ = 31.5 MV/m

G_{eff} ≈

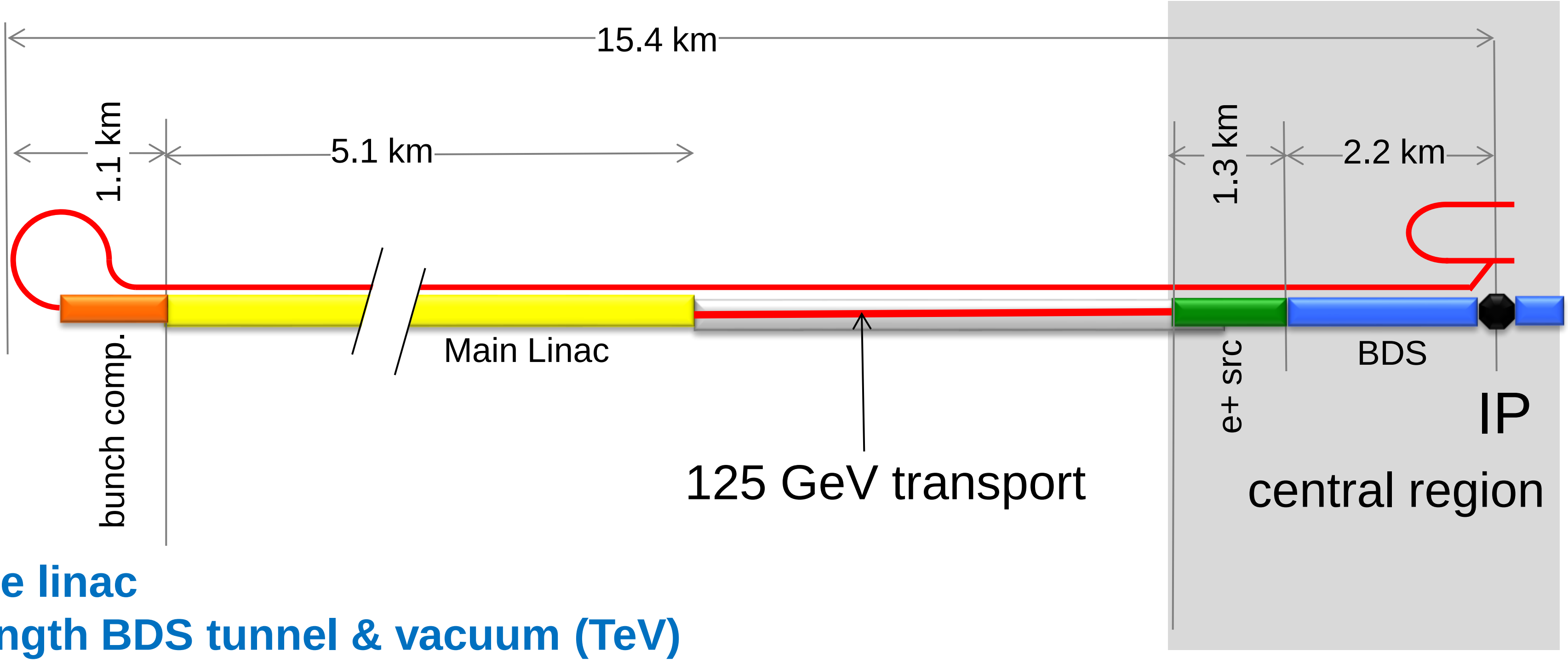


Snowmass 2005 baseline recommendation for TeV upgrade:

G_{cavity} = 36 MV/m ⇒ 9.6 km
(VT ≥ 40 MV/m)

Based on use of low-loss or re-entrant cavity shapes

250 GeV – Staged ILC

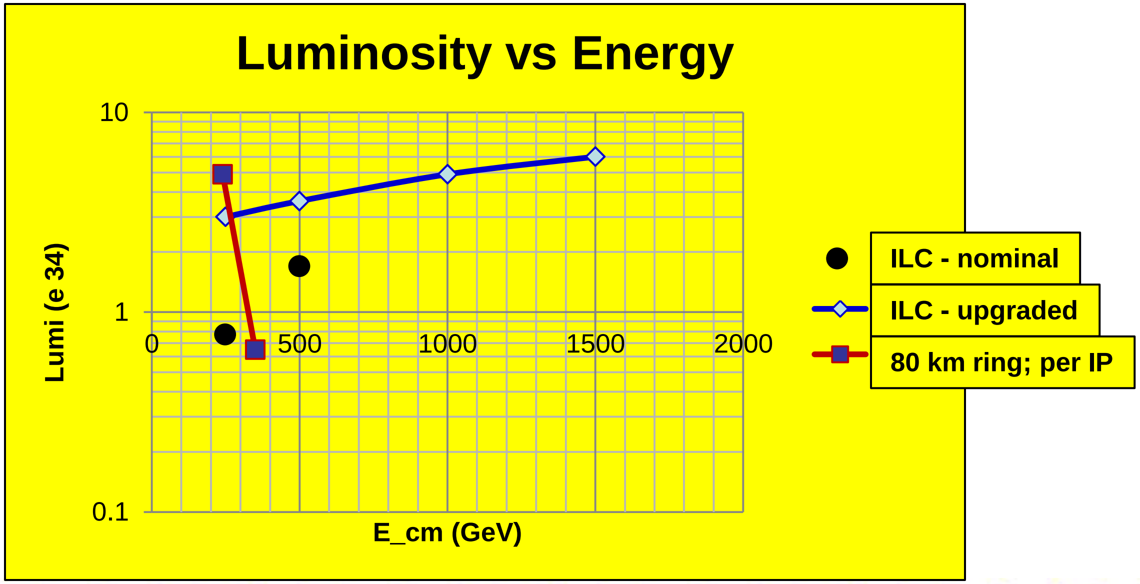


Half the linac
Full-length BDS tunnel & vacuum (TeV)
½ BDS magnets (instrumentation, CF etc)
1 RTML LTL
5km 125 GeV transport line

Extended tunnel/CFS already 500 GeV stage

ILC at low/high Ecm

- **Low E_{cm} operation of upgraded ILC:**
  - L_{250} ~ 3e34; Wall plug 200 MW
  - Possible Higgs Factory
- **High E_{cm} ~ 1.5 TeV**
  - L_{1500} ~ 6e34; Wall plug 340 MW



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Total pair energy per bunch crossing	E_{pairs}	TeV	344.1	46.5	344.1	1338.0	3441.0

Two Alternatives to ILC (1):

1. **e+/ e- storage ring-based colliders**
   - Low Energy ‘factories’
   - Assume substantial injection complex
   - Enormous tunnel complex (step toward VLHC)
   - Based on extrapolation of established technology
   - R & D needed

- **Only 2 parameters:**
   - ***Ring Size*** **and**
   - ***Site Power consumption***

Civil engineering cost and strategy →

Ring Collider Proposed Parameters

Name		LEP2 for comparison	LEP3	TLEPt	SuperTRISTAN	CW250	Summers
Circumference	km	26.7	26.7	80	60	233	15.00
Beam energy	GeV	104.5	120	175	200	250	120
Bunch population	10^10	57.5	100	75	249.2	48.5	48.5
Number of bunches/beam		4	4	12	1	41	3
Number of IP		4	2	2	1	1	1
Bunch collision frequency	kHz	44.91	44.91	44.97	5.00	52.75	65.10
geo.emit(x)	nm	48	25	20	3.2	3.6	3.6
geo.emit(y)	nm	0.25	0.1	0.1	0.017	0.00022	0.00099
betax	mm	1500	200	200	30	20	20
betay	mm	50	1	1	0.32	0.6	0.6
sigx	micron	268	71	63	9.8	8.5	8.5
sigy	micron	3.536	0.32	0.32	0.0738	0.0244	0.0244
sigz	mm	16.1	2.3	2.5	1.4	6.67	6.67
half.cross.angle	mrad	0	0	0	35	17	34
bending radius	km	3.096	2.62	9	7.65	29	1.9
radiation loss/turn	GeV	3.408	6.99	9.3	18.5	11.9	9.7
Damping partition		1.1	1.5	1	2	2	2
radiation power (2beams)	MW	22	100	100	74	98	98
Tune shift/IP (x)		0.025	0.09	0.05	0.017	0.0007	0.0014
Tune shift/IP (y)		0.065	0.08	0.05	0.155	0.23	0.2
Equilibrium energy spread	%	0.22	0.23	0.22	0.196	0.126	0.236
Luminosity per IP	10^34	0.0125	1.07	0.65	5.2	7.6	4.4

Data taken from the papers in red in the prewvious page

🟨 Not given in the reference. Computed from other values

🟦 Not given in the reference. Assumed.

From K. Yokoya

From K. Yokoya:

Proposed Ring Colliders

- Several authors suggested possibilities of e+e- ring colliders for Ecm>200GeV.
  - A) T.Sen, J.Norem, Phys.Rev.ST-AB 5(2002)031001
    C=233km tunnel for VLHC
  - B) A.Blondel and F.Zimmermann, CERN-OPEN-2011-047, Jan.2012 (Version 2.9). arXiv:1112.2518. Also IPAC12 TUPPR078.
    LEP3, DLEP.
    LEP3Day June 18. 2nd LEP3Day Oct.23 (**yesterday!**)
  - C) K.Oide, "SuperTRISTAN: A possibility of ring collider for Higgs factory", KEK meeting on 13 Feb 2012.
    SuperTRISTAN
  - D) G.Lyons, arXiv:1112.1105 [physics.acc-ph], Feb.2012.
    PhD thesis. Nanobeam version of A)
    IPAC12 TUPPR008
  - E) D.Summers, et.al. “Rapid Recycling Magnets - Tests & Simulations”, Muon Accelerator Program 2012 Winter Meeting, 4-8 Mar.2012.
    SLAC. Small ring version of D)
    See also IPAC12 TUPPR008
- There seems to be more: China, etc.

R&D Items of Ring Colliders

From K. Yokoya

- Momentum band-width
  - bucket height must be > η (OK with a bit higher V_{RF})
  - arc is OK (light sources accept > 4%)
  - FFS is not easy
    - chromaticity $L^*\eta/\beta_y^*$ larger than existing covery
    - synchrotron oscillation should be included (very rapid)
    - 2% is perhaps feasible (non-educated guess)
- Vertical emittance
  - light sources can reach ε_{gy} ~ 1pm at low energy
  - but colliders at high energy?
  - still far above the fundamental limit due to radiation opening angle ($1/\gamma$)
  - but ref D)E) assume too small emittance
- Synchrotron radiation power O(100MW)
  - 4x LEP2

Low emittance operation planned for Super KEK-B

Collider ‘Wall Plug’ **AC Power** use:

ILC and 80 km ring:	ILC -H	ILC-nom	Ring - H	Ring - t
E_cm (GeV)	250	500	240	350
SRF Power to Beam (MW)	5.2	10.5	100	100
Eff. RF Length (m)	7,837	15,674	600	1200
RF klystron peak efficiency (%)	65	65	65	65
klystron operating margin, HVPS, Klystron Aux and klystron water cooling (% inefficiency)			20*	20
Overall system RF efficiency (%)	10	14	45	45
Cryo (MW)	16	32	20	40
Normal Conducting (exc. Injector complex) (MW)	6	10	120**	120
Injector complex	32	32	16***	16
Conventional (Air, lighting, ..)	6	6****	18	18
Total (exc. detector)	**112**	**153**	**396**	**416**

*** 5% for operating margin, 2% for auxiliaries, 3% for HVPS and 10% for water cooling**
**** assume 1.5 kW / m tunnel inclusive (ILC avg. 3 kW / m)**
***** from SSC / Fermilab injector (linac + LEB + MEB); assumes LHC not needed**
****** 6 MW for 30 km beam tunnel complex; ~3x more for 80 ring**

ILC AC Power loads:

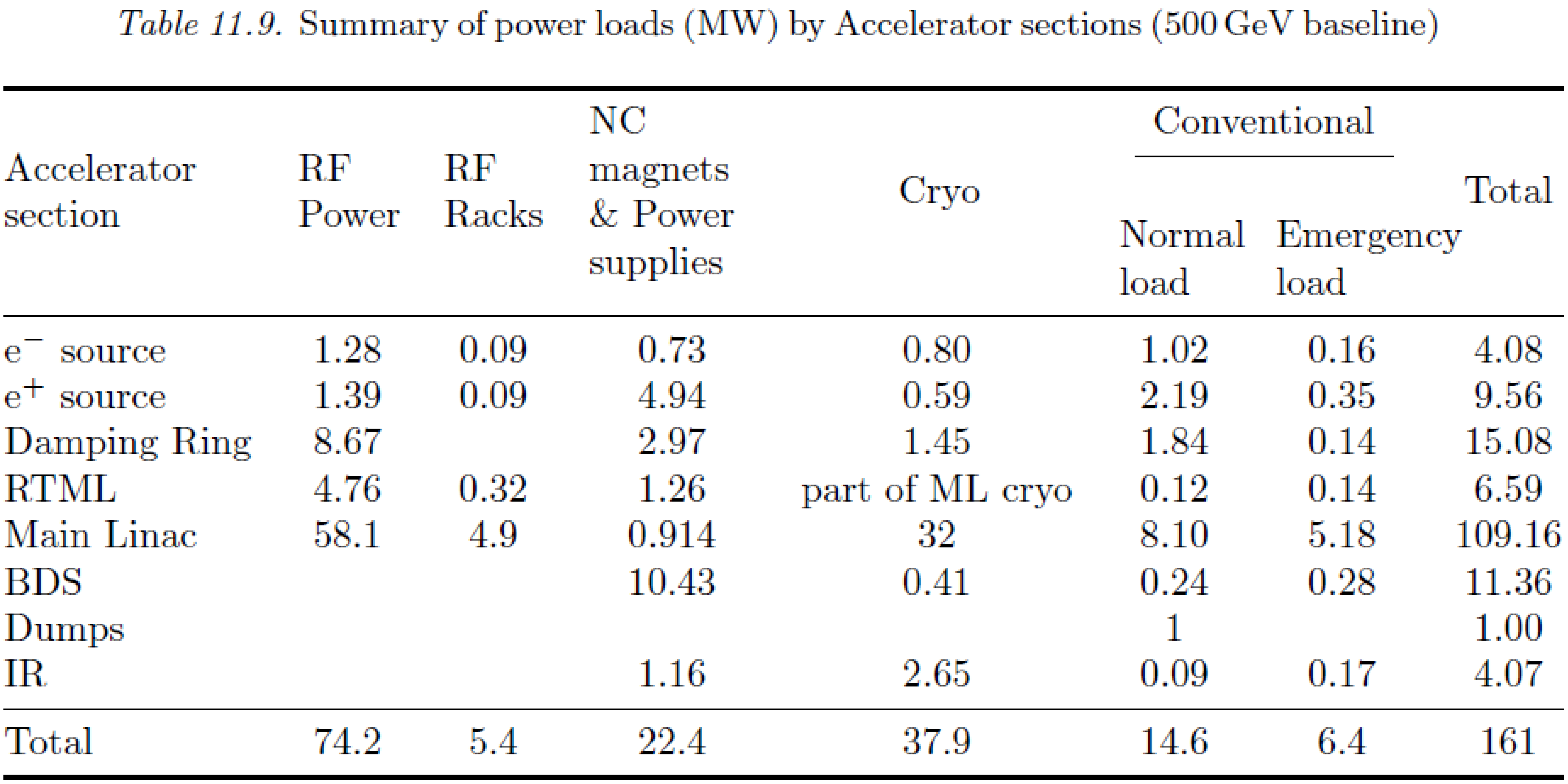


Table 11.9. Summary of power loads (MW) by Accelerator sections (500 GeV baseline)

Accelerator section	RF Power	RF Racks	NC magnets & Power supplies	Cryo	Conventional		Total
					Normal load	Emergency load	
e$^-$ source	1.28	0.09	0.73	0.80	1.02	0.16	4.08
e$^+$ source	1.39	0.09	4.94	0.59	2.19	0.35	9.56
Damping Ring	8.67		2.97	1.45	1.84	0.14	15.08
RTML	4.76	0.32	1.26	part of ML cryo	0.12	0.14	6.59
Main Linac	58.1	4.9	0.914	32	8.10	5.18	109.16
BDS			10.43	0.41	0.24	0.28	11.36
Dumps					1		1.00
IR			1.16	2.65	0.09	0.17	4.07
Total	74.2	5.4	22.4	37.9	14.6	6.4	161

Questions asked for ‘Snowmass’:

CSS2013 / P5 planning process:

- **What the required parameters and key characteristics of lepton / gamma colliders in the Higg's factory range? with physics capabilities far beyond the LHC?** ***at what cost? How does a Higgs factory scale cost-wise to a TeV scale linear collider?***

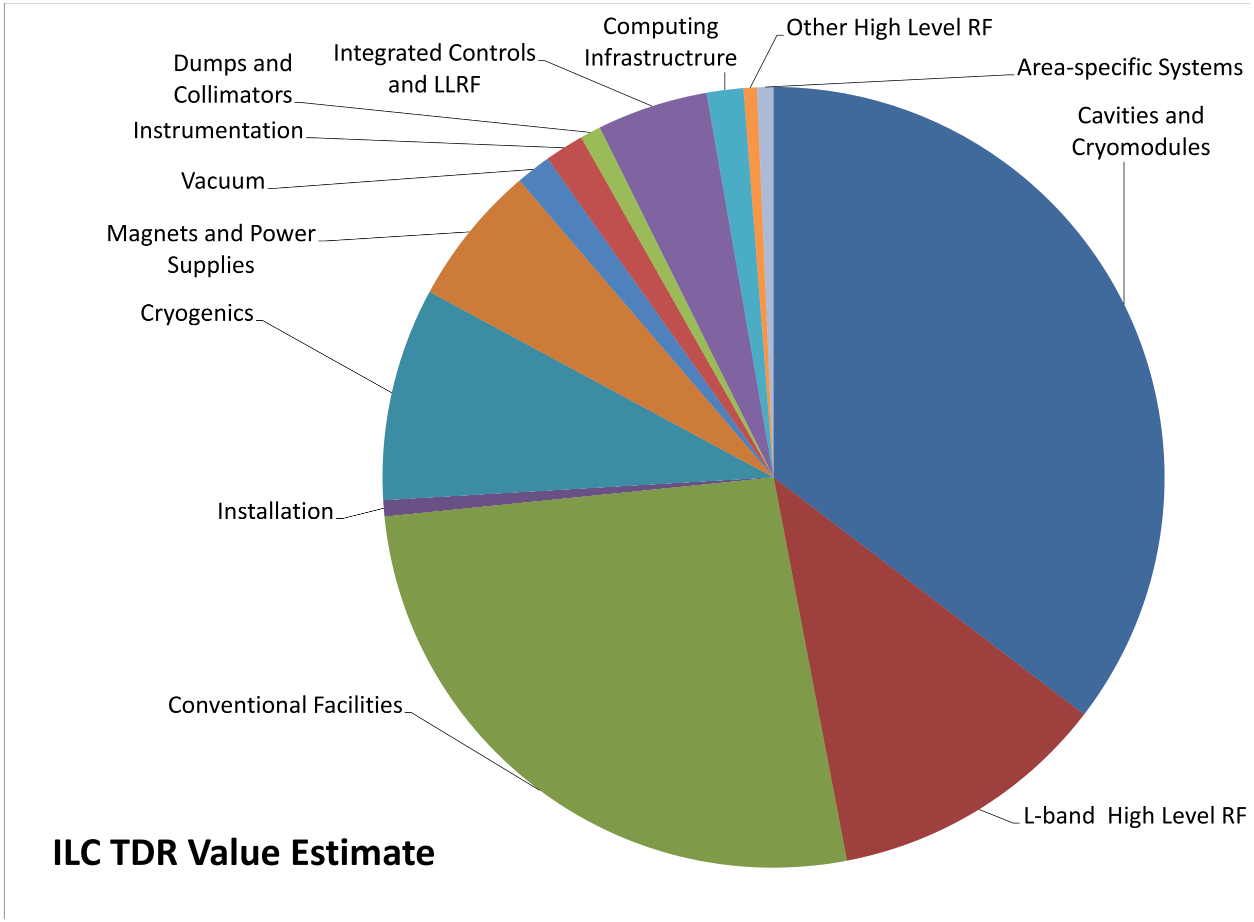
- ***<u>Cost comparisons with concepts can only be done parametrically.</u>***

ILC 'value' estimate:

'Value' is the direct cost of goods and services

Appropriate for in-kind projects

ILC: *7.8 B ILCU + 23 million labor person-hours*



Parametric 'value' costing for TeV–class machines (KILCU)*:

- **Civil Construction: 35 / m**
- **Utilities: 5000 / MW**
- **Superconducting RF 180 / m (inclusive)****
- **'Conventional Acc.' 35 / m**

		TLEP-t quantity	MILCU	ILC quantity	MILCU
Civil Construction	km	80	3000	34	1200
Power and cooling	MW	416	2000	162	800
SRF (incl. packing)	km	1.2 / .7	250	22	4000
'Conventional'	km	160	5500 ***	12	800
Installation	km	80	100	34	100
Total			**11000**		**7800****

*** 1 ILCU = USD 01.2012**
**** cryogenics not included – reuse LHC assumed; 900 MILCU included for ILC**
***** Conventional Acc. (Magnets, vacuum, etc) cost – scale reduced 2x for ring**

Institutional Labor is part of the project cost and must also be analyzed.

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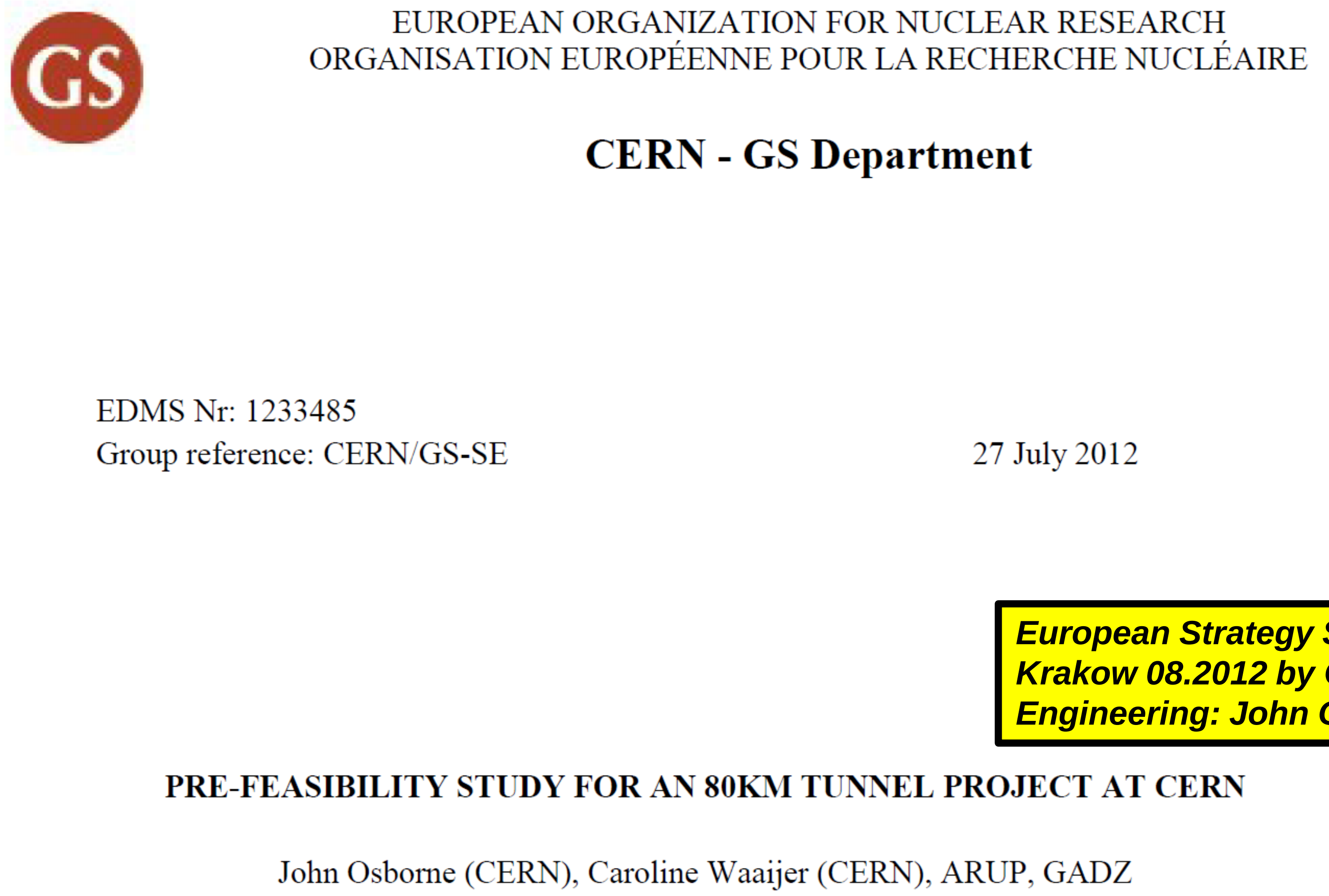

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ORGANISATION EUROPÉENNE POUR LA RECHERCHE NUCLÉAIRE

CERN - GS Department

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PRE-FEASIBILITY STUDY FOR AN 80KM TUNNEL PROJECT AT CERN

John Osborne (CERN), Caroline Waaijer (CERN), ARUP, GADZ

European Strategy Submission – Krakow 08.2012 by CERN Civil Engineering: John Osborne

Presented at:

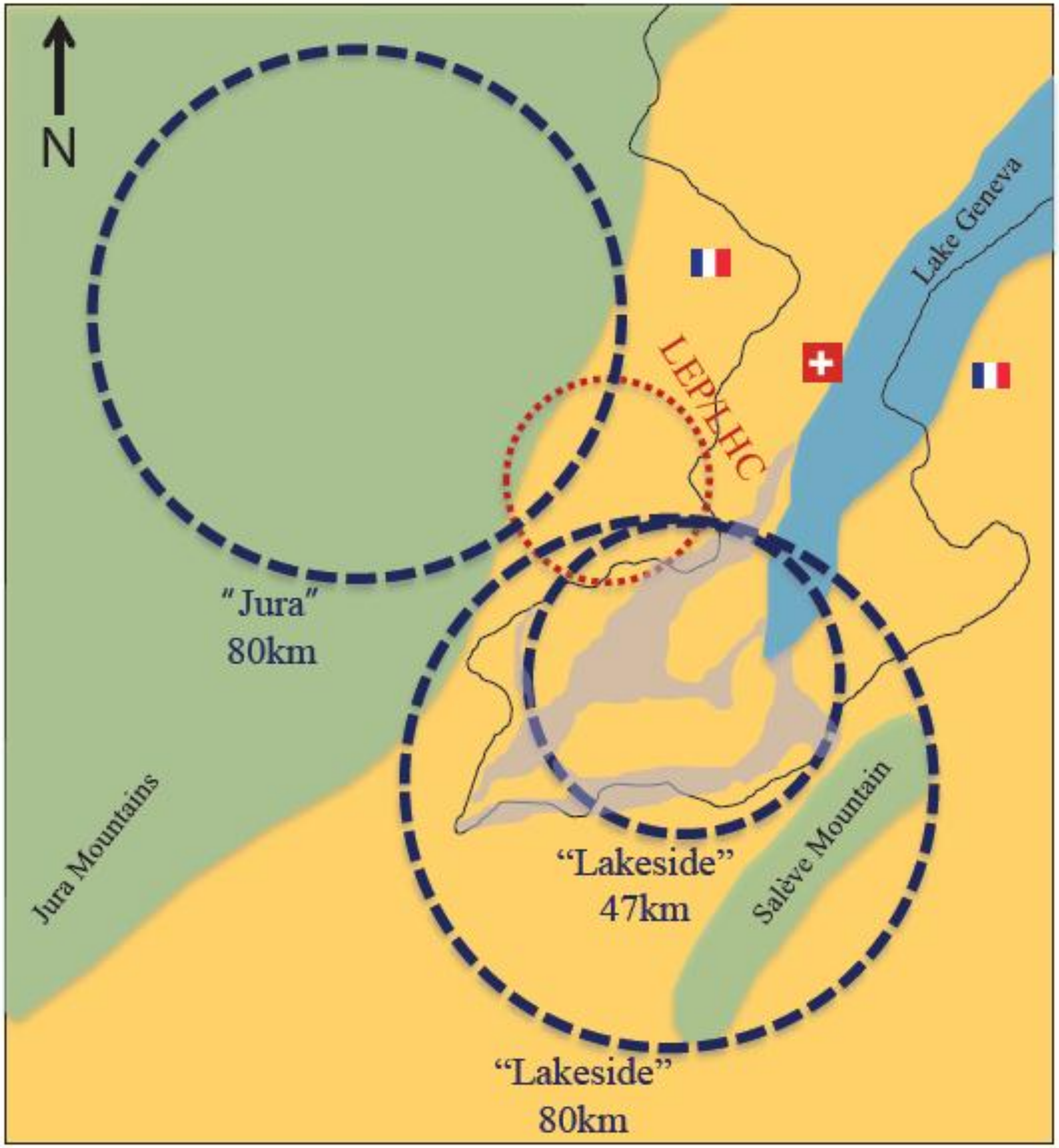
Joint Snowmass-EuCARD/AccNet-HiLumi LHC meeting 'Frontier Capabilities for Hadron Colliders 2013'

chaired by Lucio Rossi (CERN), William Barletta

from Thursday, February 21, 2013 at **09:00** to Friday, February 22, 2013 at **14:20** (Europe/Zurich)
at **CERN (40-S2-D01 - Salle Dirac)**
40-S2-D01

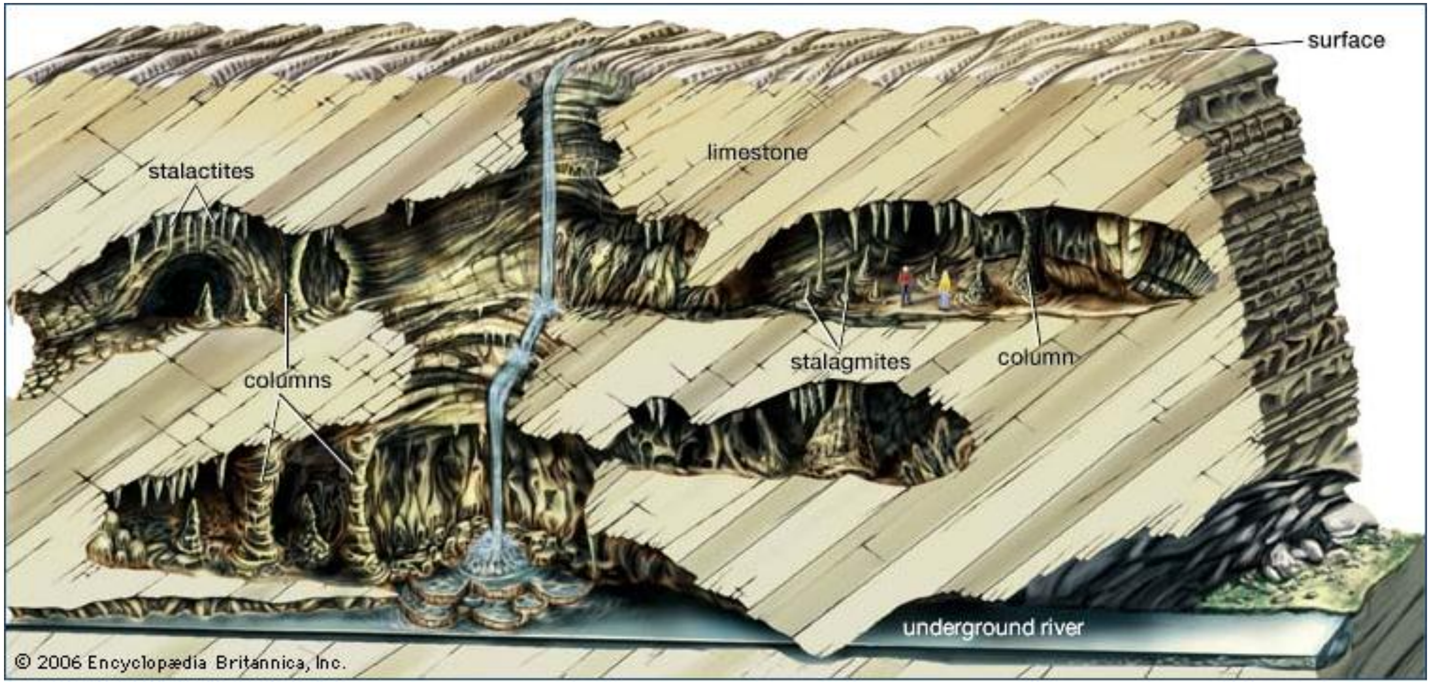
Jura & Salève: Karst Geology

- **Tunneling risk**
- **Karst (green):**
  - “Dissolution by layers of soluble bedrock, typically limestone”
  - “rocky ground, caves, sinkholes, underground rivers, and the absence of surface streams and lakes”
  - France; Kwangsi in China; Yucatán Peninsula; Florida in the United States



Karst geology:

Florida US
03.2013



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CE considerations

Tunneling

Geneva plain
Underneath Lake Geneva
Through Jura and Salève Mountains

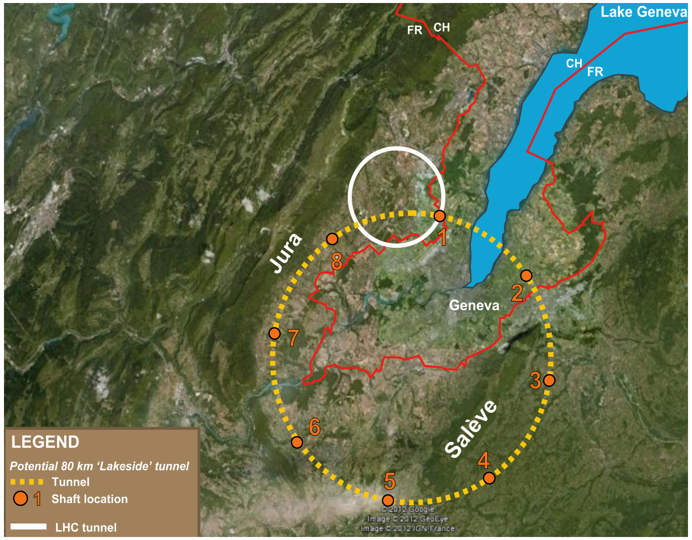
- **Mountain area** consists of Limestones and evaporates
    - For 10% of tunnel
    - Difficult tunneling conditions
        - Local and unpredictable karst features
            - » Water conduits
            - » High flow rates (600L/ sec)
        - Water transports silt-clay sediments
            - » Difficult to drawing off water through pressure relief holes
            - » Increase of water inflow over time
            - » Difficulties in removal of the water
            - » Risk of aquifer pollution & depletion
        - Anhydrites -> ‘badrock’ causes swelling
            - » Heaving of the tunnel invert
            - » Structural instabilities
            - » Probably low risk for 80km Lakeside option but high risk for 80km Jura option

LEP tunnel collapse

Example of tunnel invert heave Chienberg tunnel, Switzerland

Potential locations

- Pre-feasibility study performed by CERN and the specialized firm ARUP.
  - Focused on
    - geology & hydrogeology,
    - tunneling & construction,
    - environmental impacts



  - Result: for the 80km long tunnel location 2 '**80km Lakeside**' is most feasible.

Risk

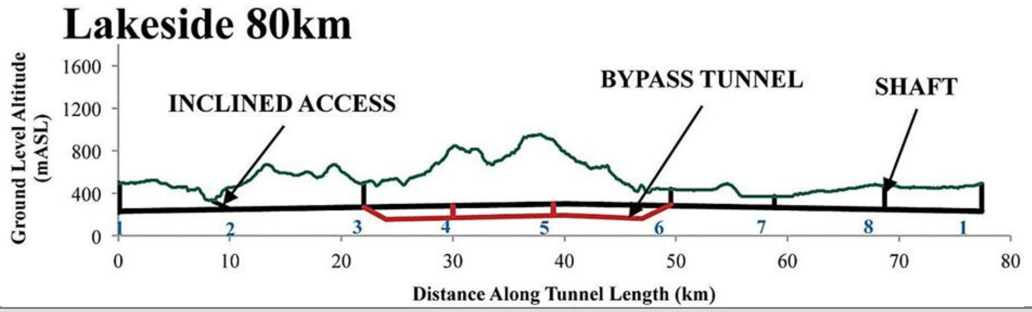
	water ingress	heaving ground	weak marls	hydro carbons	support & lining	ground response & convergence	hydrostatic pressure & drainage	Pollution of aquifers	effect of shafts on nature	effects of shafts on urban areas	**Total**
Jura 80	5	3	0	0	5	4	5	5	4	2	**33**
Lake 80	2	0	3	3	3	3	2	2	3	2	**23**
Lake 47	1	0	2	2	2	2	1	1	2	5	**18**

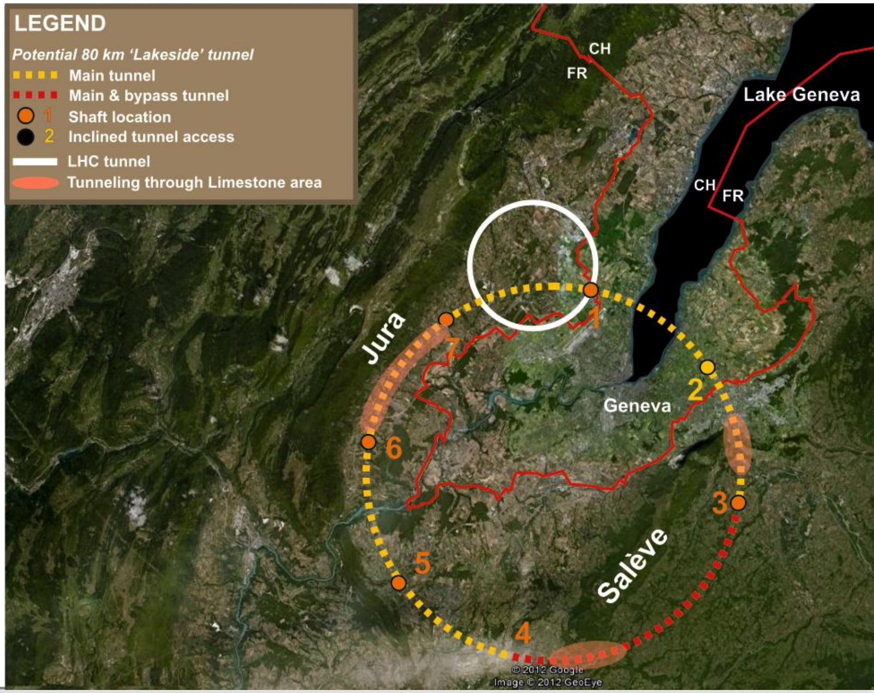
Feasibility
Low
↓
High

CE considerations Optimization

- Optimization studies for the project configuration have been started
  - Bypass tunnel in geological and environmental sensitive area
  - Inclined access tunnel in urban area

- More optimization studies needed
  - Incline tunnel?
  - More bypass tunnels?





Ring Collider R & D items:

- **Much related beam physics will be studied at Super KEK-B (2015 →)**
  - IR optics and vertical emittance will be checked. SuperKEKB will try to x10 smaller vert emittance (than LEP) with full beam-beam.
- **CERN-region ring ‘optimization’ work**
  - Avoiding Karst geology (conclusion of 21.02 meeting)
- **Large ring cost is not substantially smaller than ILC**
  - Energy consumption is excessive

Two Alternatives to ILC (2):

2. Muon colliders

- Very High energy without enormous tunneling

Basic R & D needed in four technical areas

1. Normal Conducting RF
2. Superconducting RF
3. High Field magnets
4. Targeting

System demonstrations:

1. beam cooling and
2. high power-on-target

The U.S. Muon Accelerator Program

Mark Palmer

Frontier Facilities Meeting
University of Chicago

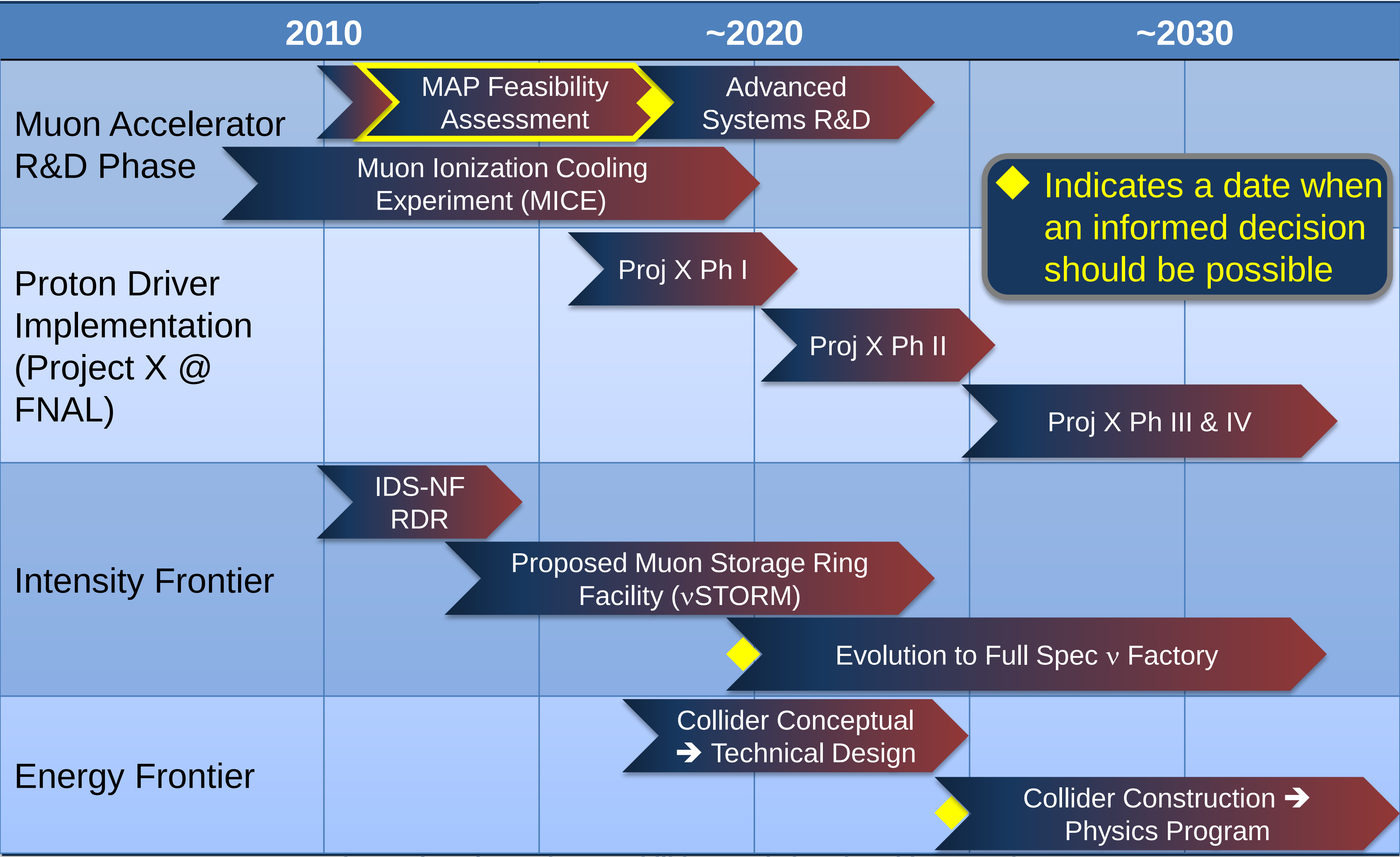
February 25, 2013

Muon Accelerators

Accelerator	Energy Scale	
Cooling Channel	**~200 MeV**	
MICE	*160-240 MeV*	←
Muon Storage Ring	**3-4 GeV**	
nSTORM	*3.8 GeV*	
Intensity Frontier n Factory	**10-25 GeV**	
Low Energy NF	*10 GeV*	
IDS-NF 2.0	*25 GeV*	
Current IDS-NF	*10 GeV*	←
s-Channel Higgs Factory	**~126 GeV CoM**	←
Energy Frontier m Collider	**> 1 TeV CoM**	
Opt. 1	*1.5 TeV CoM*	←
Opt. 2	*3 TeV CoM*	←
Opt. 3	*6 TeV CoM*	

Program Baselines

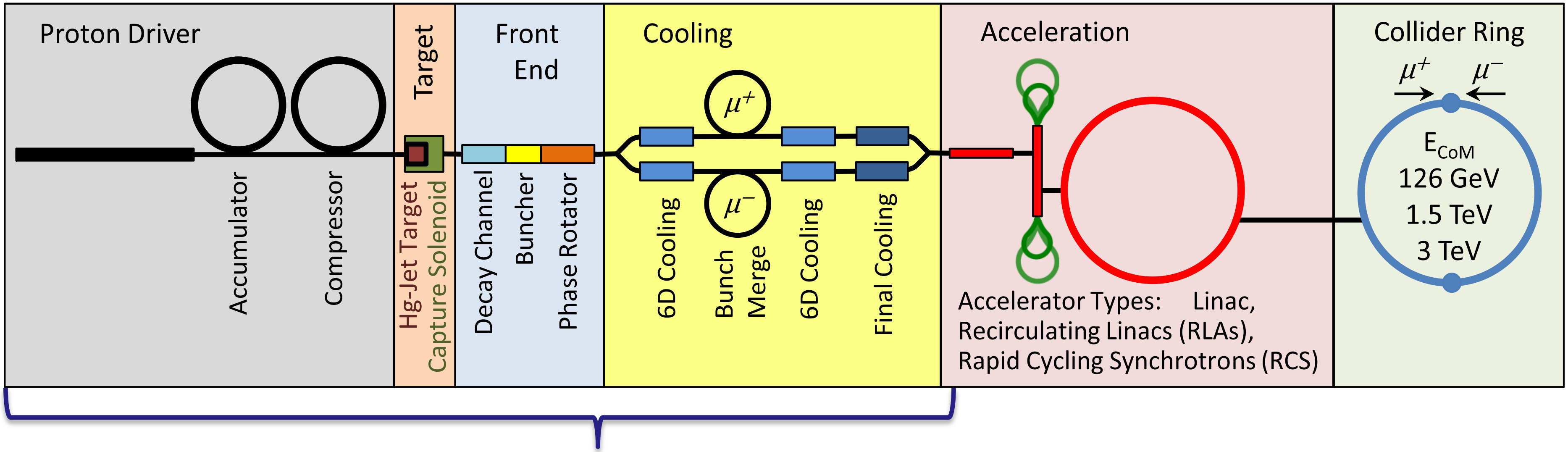
The Muon Accelerator Program Timeline



◆ Indicates a date when an informed decision should be possible

Muon Collider Concept

Muon Collider Block Diagram



Proton source:
For example PROJECT X at 4 MW, with 2±1 ns long bunches

Goal:
Produce a high intensity μ beam whose 6D phase space is reduced by a factor of ~10^6-10^7 from its value at the production target

Collider: $\sqrt{s} = 3$ TeV
Circumference 4.5km
$L = 3\times10^{34}\ \text{cm}^{-2}\text{s}^{-1}$
μ/bunch = $2\text{x}10^{12}$
$\sigma(p)/p = 0.1\%$
$\varepsilon_{\perp N} = 25\ \mu\text{m}$, $\varepsilon_{||N} = 70$ mm
$\beta^* = 5$mm
Rep. Rate = 12 Hz

Muon Collider Parameters

Muon Collider Baseline Parameters

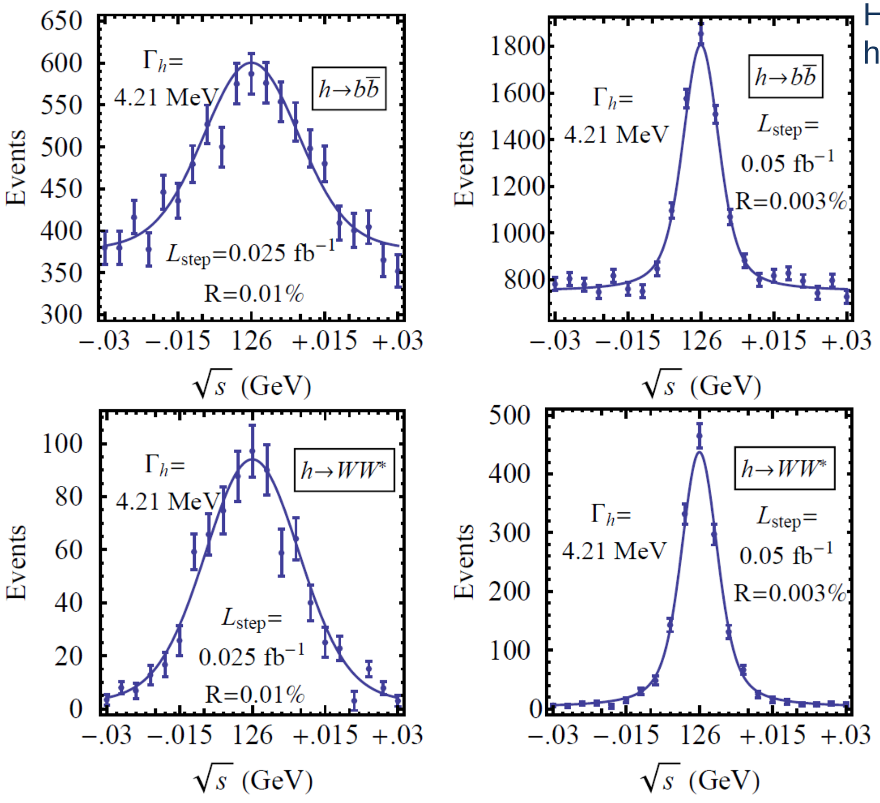
Parameter	*Units*	**Higgs Factory** Initial Cooling	 Upgraded Cooling / Combiner	**Multi-TeV Baselines**	
CoM Energy	TeV	0.126	0.126	1.5	3.0
Avg. Luminosity	10^{34}cm^{-2}s^{-1}	0.0017	0.008	1.25	4.4
Beam Energy Spread	%	0.003	0.004	0.1	0.1
Circumference	km	0.3	0.3	2.5	4.5
No. of IPs		1	1	2	2
Repetition Rate	Hz	30	15	15	12
b*	cm	3.3	1.7	1 (0.5-2)	0.5 (0.3-3)
No. muons/bunch	10^{12}	2	4	2	2
No. bunches/beam		1	1	1	1
Norm. Trans. Emittance, e_{TN}	mm-rad	0.4	0.2	0.025	0.025
Norm. Long. Emittance, e_{LN}	mm-rad	1	1.5	70	70
Bunch Length, s_s	cm	5.6	6.3	1	0.5
Beam Size @ IP	mm	150	75	6	3
Beam-beam Parameter / IP		0.005	0.02	0.09	0.09
Proton Driver Power	MW	4[♯]	4	4	4

[♯] Could begin operation at lower beam power (eg, with Project X Phase 2 beam)

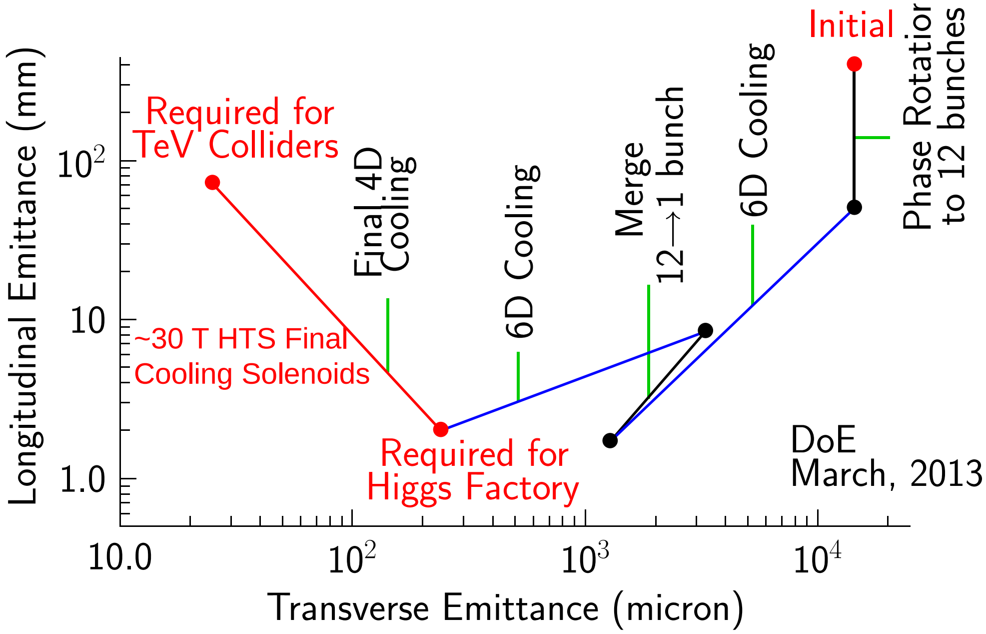
3-4 MeV CoM Energy Spread

126 GeV Higgs Factory

s-channel coupling of Muons to HIGGS with high cross sections:
Muon Collider of with L = 10^{32} cm^{-2}s^{-1} @ 63 GeV/beam (50000 Higgs/year)
Competitive with e+/e- Linear Collider with L = 2. 10^{34} cm^{-2}s^{-1} @ 126 GeV/beam



Han and Liu
hep-ph 1210.7803



Reduced cooling:
$\varepsilon_{\perp N}$ =0.3π·mm·rad,
$\varepsilon_{\parallel N}$ =1π·mm·rad

Major advantage for Physics of a $\mu^+\mu^-$ Higgs Factory: possibility of direct measurement of the Higgs boson width (Γ~4MeV FWHM expected)

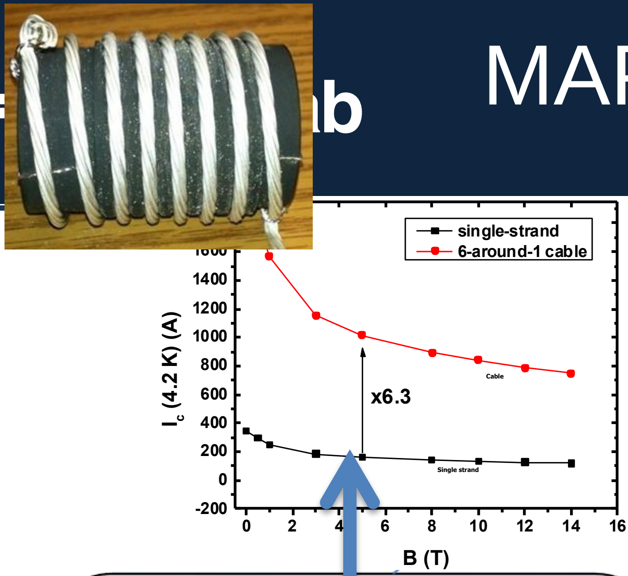
Fermilab

Overview of R&D Areas

- Design Studies
  - Proton Driver
  - Front End
  - Cooling
  - Acceleration and Storage
  - Collider
  - Machine-Detector Interface
  - Work closely with physics and detector efforts
- Major System Demonstration
  - The Muon Ionization Cooling Experiment – MICE
    - Major U.S. effort to provide key hardware: RF Cavities and couplers, Spectrometer Solenoids, Coupling Coils
    - Experimental and Operations Support

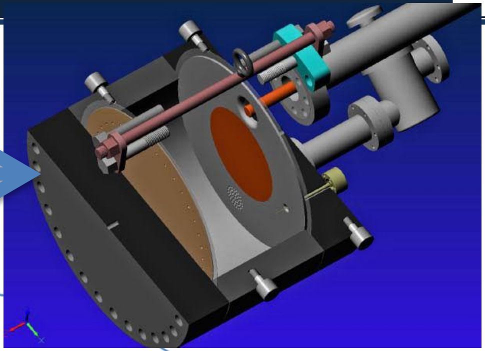
- Technology R&D
  - Normal Conducting RF
    - Vacuum RF Cavities with reduced breakdown rates in high magnetic fields
    - Cavity Materials
    - RF Cavities filled with high pressure gas
  - Superconducting RF
    - Demonstrating good Q_0 performance with Niobium on Copper cavities
      - Performance
      - Fabrication techniques
  - Magnets
    - High field solenoids for cooling channel application
    - 10T dipole design (synergistic with LHC upgrade activities)
    - Rapid cycling magnets for high energy hybrid synchrotron
    - Shielded magnets for μ decay in rings
  - Target and Absorbers
    - Liquid jet targets capable
    - Capture solenoid technology

MAP Technology Highlights



Successful Operation of 805 MHz "All Seasons" Cavity in 3T Magnetic Field under Vacuum

MuCool Test Area/Muons Inc



Breakthrough in HTS Cable Performance with Cables Matching Strand Performance

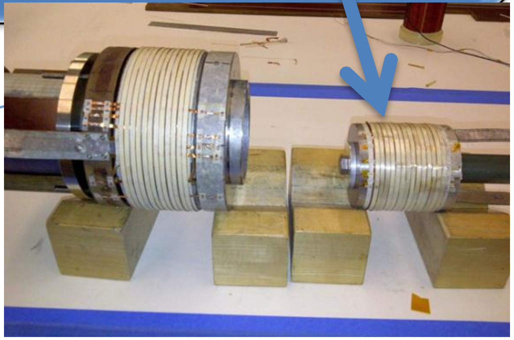
FNAL-Tech Div
T. Shen-Early Career Award

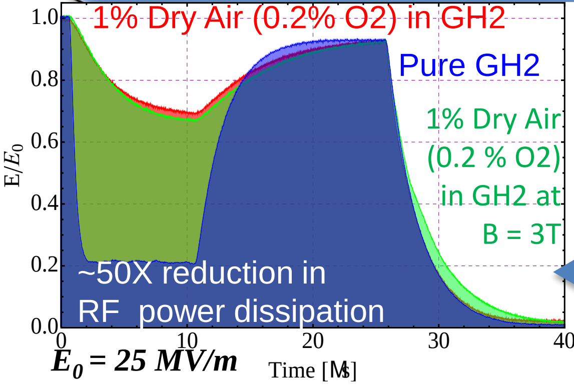
The Path to a Viable Muon Ionization Cooling Channel

World Record HTS-only Coil

15T on-axis field
16T on coil

PBL/BNL





Demonstration of High Pressure RF Cavity <u>in 3T Magnetic Field with Beam</u>

Extrapolates to μ-Collider Parameters

MuCool Test Area

Muon collider R & D

Summary: