CERN Future Circular Colliders Study

Frank Zimmermann

International Workshop on Future High Energy Circular Colliders
IHEP Beijing,
16 December 2013

Many thanks to Roy Aleksan, Michael Benedikt (FCC Design Study Coordinator), Alain Blondel (FCC Kick-Off LOC Chair), Frederick Bordry (new CERN DAT), Luca Bottura, Francesco Cerutti, John Ellis, Hector Garcia, Cedric Garion,, Bernhard Holzer, Patrick Janot, Erk Jensen, Eberhard Keil, Roberto Kersevan, Max Klein, Mike Koratzinos, Luisella Lari, Eugene Levichev, Nicolas Mounet, Robert Rimmer, Daniel Schulte, Valery Telnov, Rogelio Tomas, Jörg Wenninger

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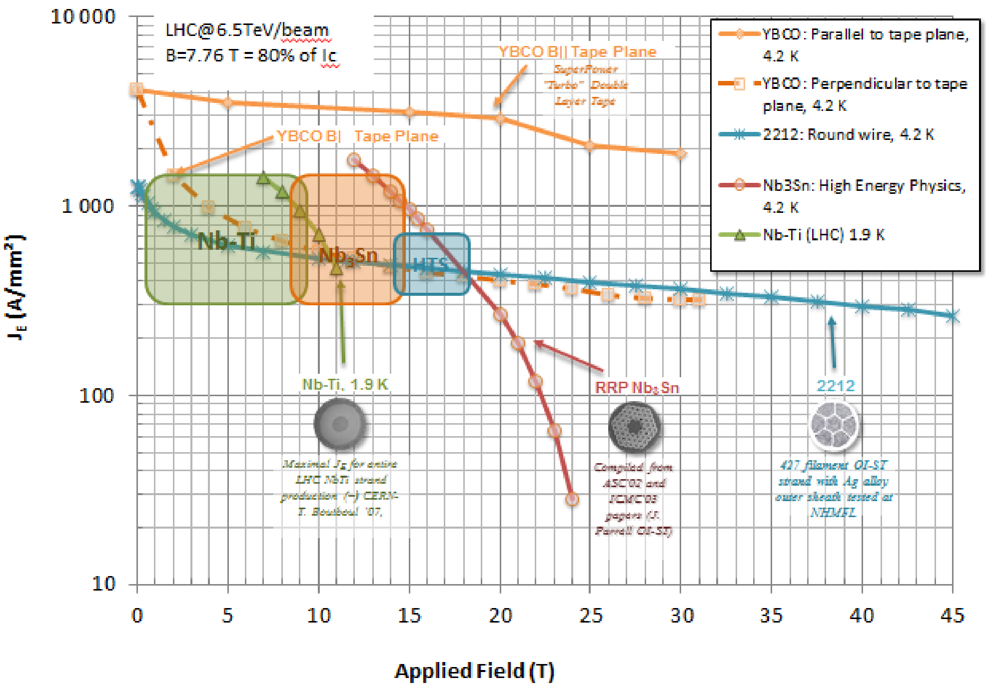
European Strategy Update (ESU) on Particle Physics
Design studies and R&D at the energy frontier

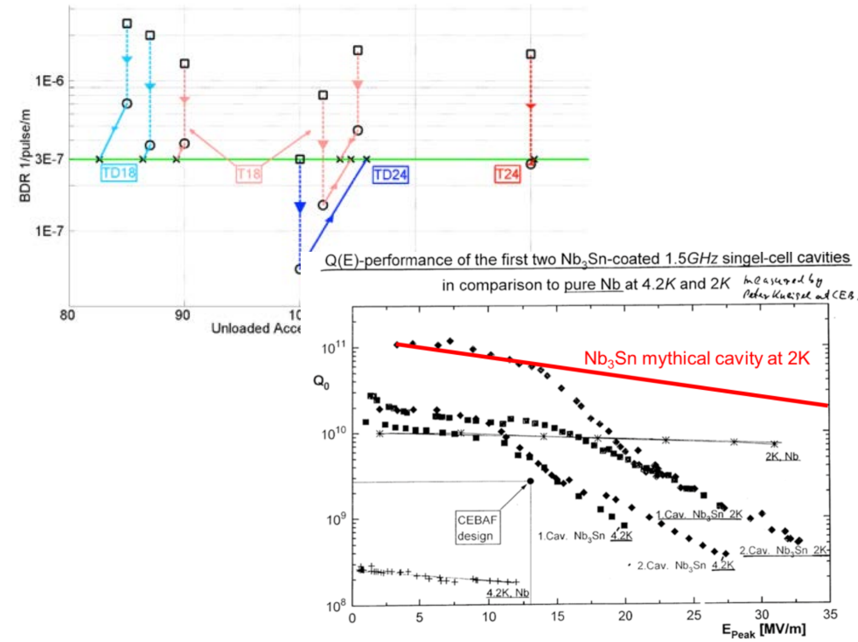
"to propose an ambitious **post-LHC accelerator project at CERN** by the time of the next Strategy update":

d) *CERN should undertake design studies for accelerator projects in a global context,*

*with emphasis on **proton-proton and electron-positron high-energy frontier machines**. These design studies should be coupled to a vigorous accelerator **R&D programme**, including **high-field magnets** and **high-gradient accelerating structures**, **in collaboration with national institutes, laboratories and universities worldwide.***



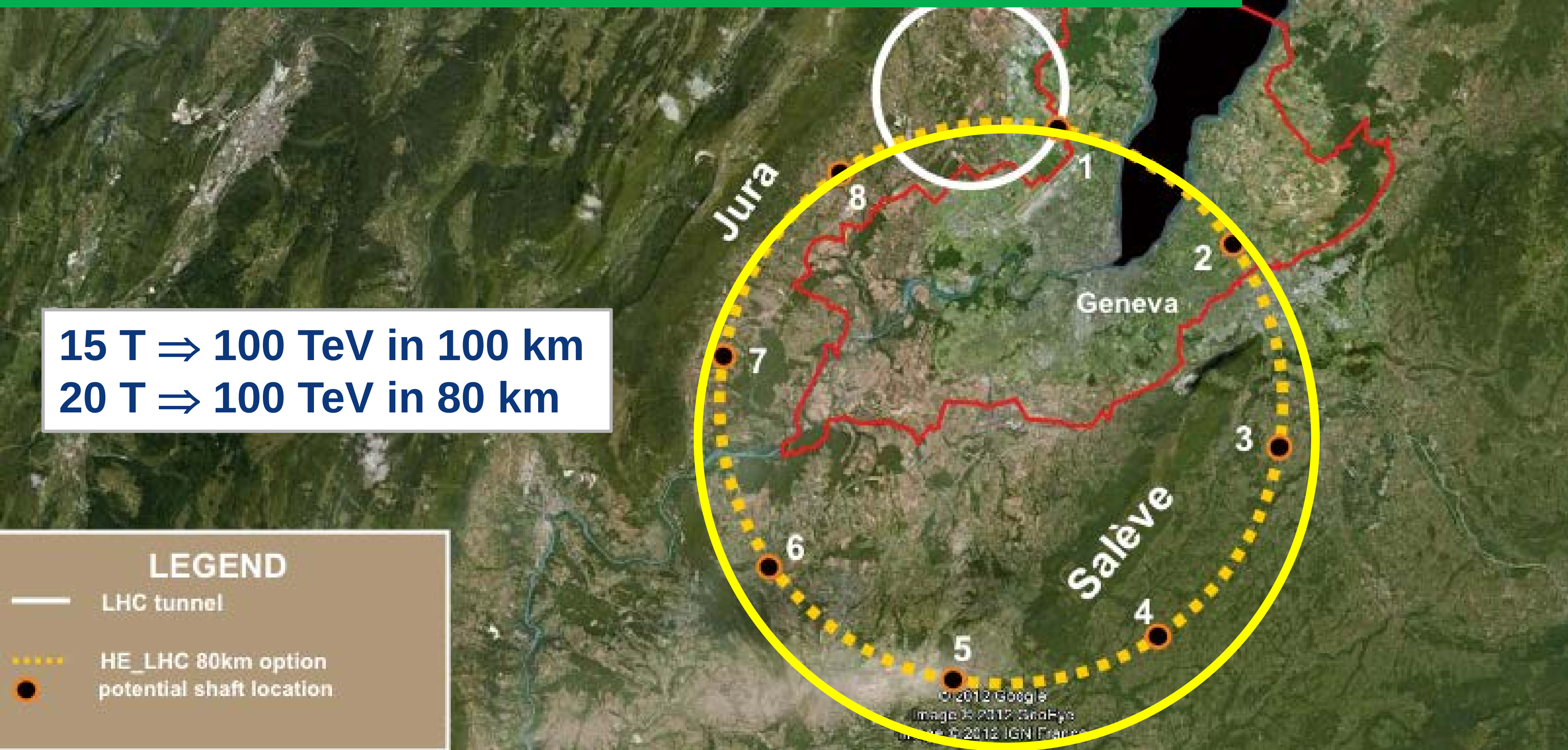
high-field magnets: VHE-LHC/FHC



high-gradient acceleration: CLIC and TLEP/FLC

FCC Study (Future Circular Colliders)
CDR and cost review for the next ESU (2018)

- 80-100 km tunnel infrastructure in Geneva area
- design driven by pp-collider requirements
- with possibility of e+-e- (TLEP) and p-e (VLHeC)
- CERN-hosted study performed in international collaboration



15 T ⇒ 100 TeV in 100 km
20 T ⇒ 100 TeV in 80 km

Kick-Off Meeting for FCC Study

- To prepare international collaborations, study scope and topics will be discussed in kick-off meeting at U. Geneva 12-15 February 2014
- CERN would like to promote global collaboration of future circular collider studies

UNIVERSITÉ DE GENÈVE CERN FCC

Future Circular Colliders Study Kickoff Meeting

12-15 February 2014
University of Geneva, Geneva
Europe/Zurich timezone

Search

Future Circular Colliders Kickoff Meeting

http://indico.cern.ch/e/fcc-kickoff

- Earlier topical workshops on HE-LHC (2010), LEP3/TLEP (6 meetings in 2012-13) and VHE-LHC (2013) in the frame of EuCARD
- Kick-off meeting covers accelerator, detectors, physics case, technology, infrastructure & tunnel construction
- Total no. of participants limited to 500 (early registration suggested)

FCC Study Scope and Structure

Future Circular Colliders - Conceptual Design Study for next European Strategy Update (2018)

Infrastructure

tunnels, surface buildings, transport (access roads), civil engineering, cooling ventilation, electricity, cryogenics, communication & IT, fabrication and installation processes, maintenance, environmental impact and monitoring,

Hadron injectors

Beam optics and dynamics
Functional specs
Performance specs
Critical technical systems
Operation concept

Hadron collider

Optics and beam dynamics
Functional specifications
Performance specs
Critical technical systems
Related R+D programs
HE-LHC comparison
Operation concept
Detector concept
Physics requirements

e+ e- collider

Optics and beam dynamics
Functional specifications
Performance specs
Critical technical systems
Related R+D programs
Injector (Booster)
Operation concept
Detector concept
Physics requirements

e- p option: Physics, Integration, additional requirements

Team preparing FCC Kick-Off & Study

Future Circular Colliders - Conceptual Design Study
Study coordination, host state relations, global cost estimate
M. Benedikt, F. Zimmermann

Hadron injectors **B. Goddard**	**VL Hadron collider** **D. Schulte**	**Infrastructure, cost estimates** **P. Lebrun**	**e+ e- collider** **J. Wenninger**	High Field Magnets **L. Bottura**	**Physics and experiments**
				Supercon-ducting RF **E. Jensen**	Hadron physic Experiments, infrastructure **A. Ball, F. Gianotti, M. Mangano**
				Cryogenics **L. Tavian**	
	e- p option Integration aspects **O. Brüning**			Specific Technologies (MP, Coll, Vac, BI, BT, PO) **JM. Jimenez**	e+ e- exper., physics **A. Blondel J.Ellis, P.Janot**
Operation aspects, energy efficiency, OP & mainten., safety, environment. **P. Collier**					
Planning (Implementation roadmap, financial planning, reporting) **F. Sonnemann**					e- p physics + **M. Klein**

Main Parameters for FHC *(VHE-LHC)*

- Energy **100 TeV c.m.**
- Dipole field **15 T** (baseline) [20 T option]
- Circumference ~ 100 km
- #IPs 2+2
- Beam-beam tune shift 0.01 (total for 2 IPs)
- Bunch spacing 25 ns [5 ns option]
- Bunch population (25 ns) 10^{11}–2×10^{11} (beam current 0.5-1 A)
- Normalized rms emittance 2.2 μm
- Luminosity 5×10^{34} $cm^{-2}s^{-1}$
- β^* 1.1 m [2 m conservative option]
- Synchroton radiation arc 26 W/m/ap. [arc fill factor 78%]
- Stored beam energy 8.3 GJ/beam
- Longit. emit damping time 0.5 h
- Straight section length 1400-2000 m (8 or 12)
- Option: Polarized proton beams (with Siberian snakes)

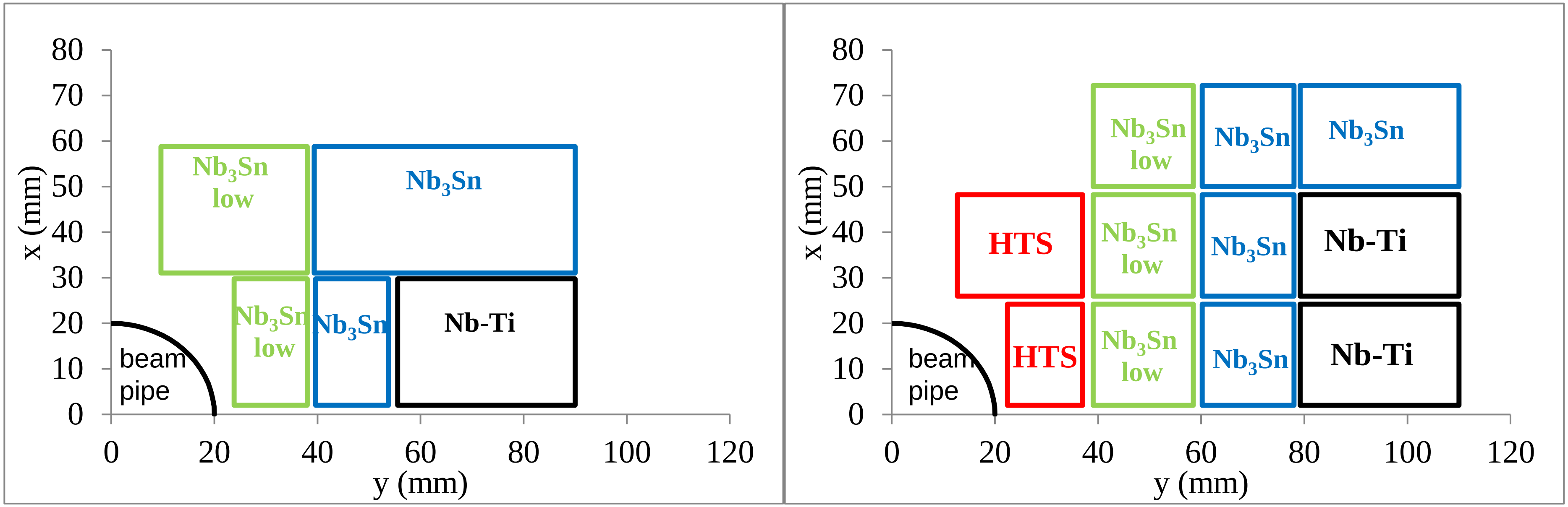
preliminary

Some FHC Challenges

- **High-field SC magnet system**
- **Vacuum system & synchrotron radiation heat load**
  - ***warm photon absorbers in dipole interconnects? antechamber,*** *higher-T beam screen?* ***Vacuum stability, impedance, e- cloud, bunch spacing***
- Synchrotron radiation **damping**
  - *controlled blow up? shorter bunch spacing? crab waist collisions??*
- **Luminosity limits**
  - *Radiation damage, pile up, bunch spacing, detector technology*
- **Machine protection**
  - *Energy in beam & magnets, dump, collimation; quench protection*
- **Optics**
  - *Maximizing fill factor, IR design & length (&#) of straight section*

Cost-Optimized Magnets for FHC

15-T dipole 20-T dipole

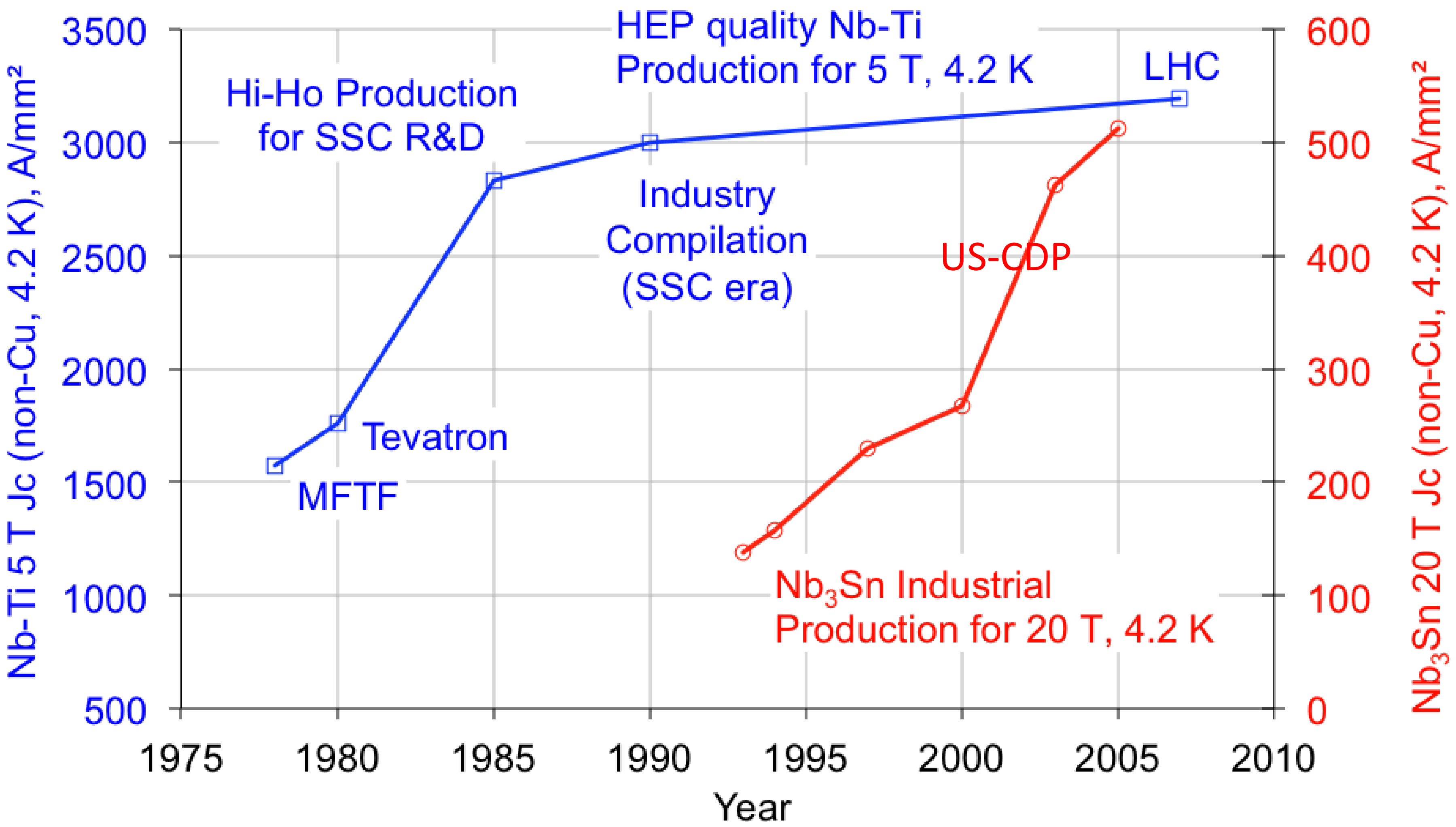


15 T dipoles + 100 km circumference

→ 100 TeV *pp*

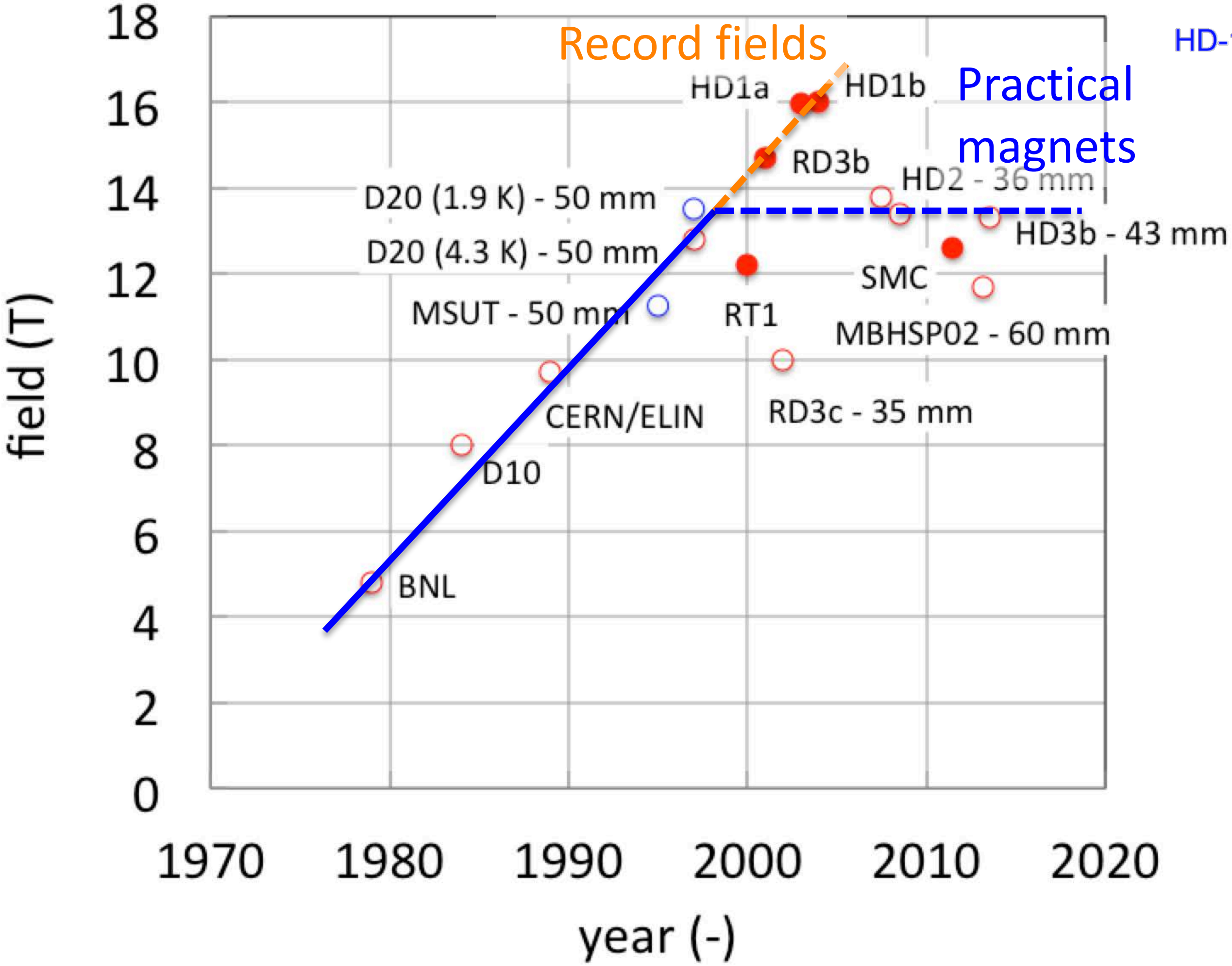
E. Todesco, L. Rossi, P. McIntyre

Evolution of *Nb-Ti* & *Nb_3Sn* SC Cable



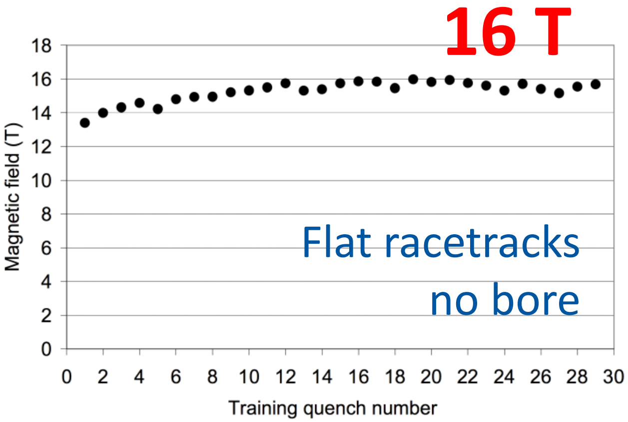
L. Bottura (CERN), J. Parrell (OST)

High-Field Dipoles



LBNL Superconducting Magnet Program
Accelerator and Fusion Research Division
Newsletter
October 2003
Issue No. 2

HD-1 Sets New Dipole Field Record

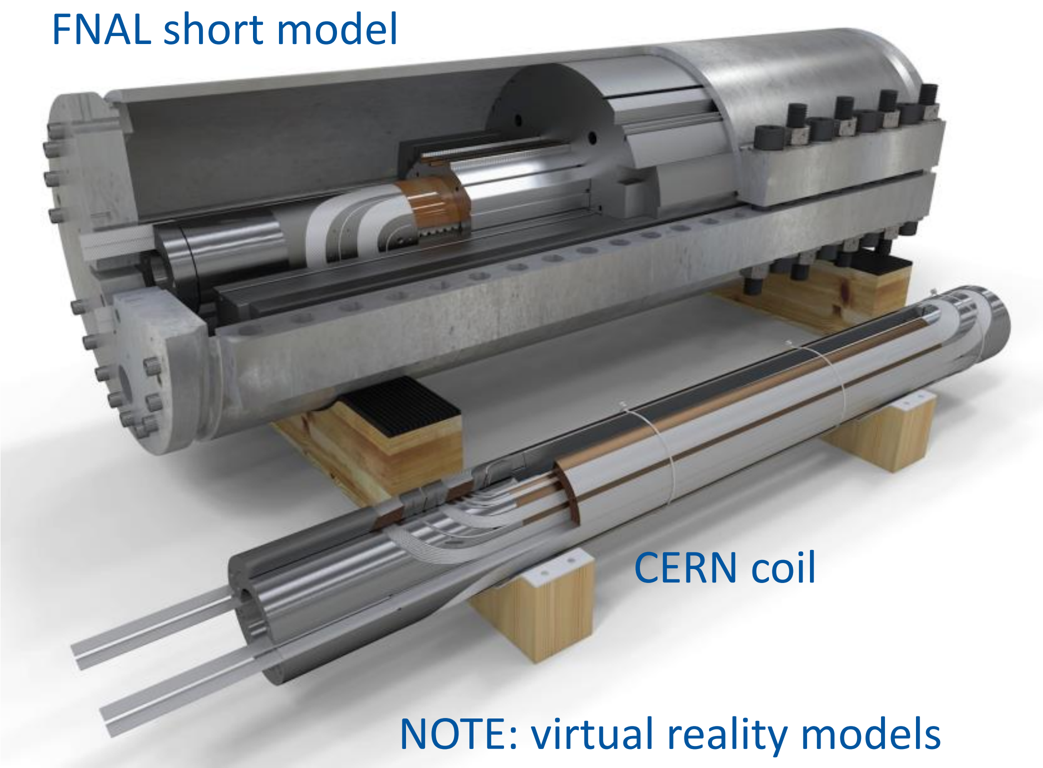


Data by courtesy of L. Rossi (CERN) and S. Caspi (LBNL)

11-T accelerator dipoles for HL-LHC

- Demonstrate the required performance (11.25 T at 11850 A)
- Achieve accelerator field quality
- Study in depth mechanics and manufacturing
- Address specific issues such as quench protection

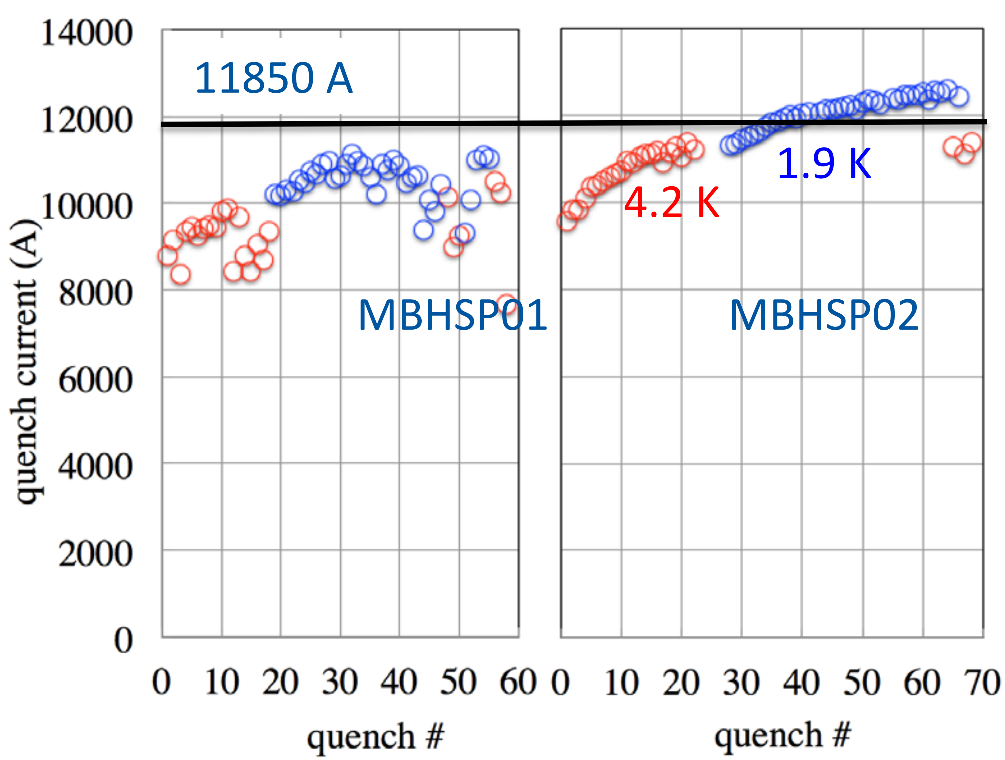
Next 2 years !



L. Bottura (CERN), D. Mitchell, F. Nobrega (FNAL), M. Karppinen (CERN)

HL-LHC 11-T performance so far

- Encouraging results !
  - B_{max}= 11.7 T (78% of expected SSL at 1.9 K)
  - Improving field quality (reduced sub-element diameter, cored cable)
- Future work:
  - Ramp-rate quench dependence
  - Holding current quenches
  - Geometric harmonics



L. Bottura (CERN), G. Chlachidze, J. Di Marco, images E. Barzi (FNAL)

FHC – extracting SR heat

SR heat load 3 MW total;

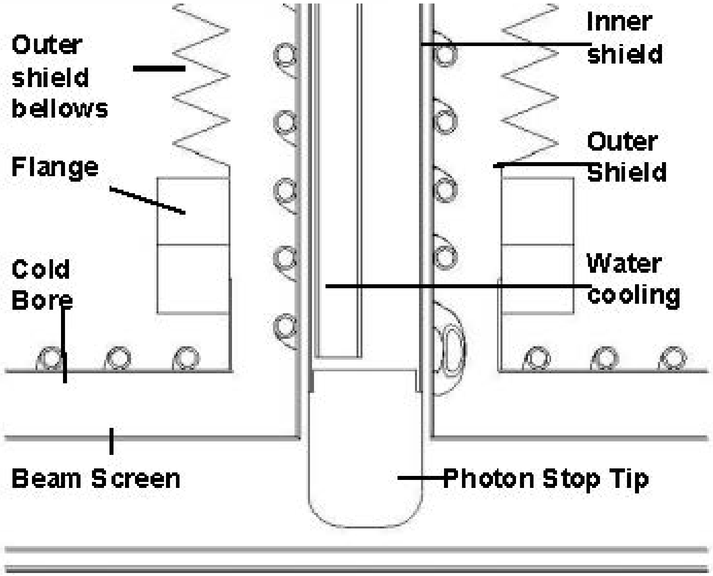
26 W/m/aperture

one option: dedicated warm photon stops in magnet interconnects

as developed by FNAL for VLHC

M. Geynisman et al., “Report on the First VLHC Photon Stop Cryogenic Design Experiment,” Advances in cryogenic engineering, Anchorage, AIP Conf.Proc. 710 (2004) 379-388 ;

Also P. Bauer et al., "Report on the First Cryogenic Photon Stop Experiment," FNAL TD-03-021, May 2003



with or w/o anterchamber

FHC beam power & collimation

Energy stored: 8 GJ per beam (LHC: 0.4 GJ)

- beam dumping system design, interlock system

Collimation

- higher energy density: more robust materials?
  collimators are first hit by beam in case of failure; LHC collimators made from fibre-reinforced carbon (CFC); for FHC more robust composite materials?
- cleaning efficiency degrading with beam energy
  collimators minimize beam loss in the cold regions; nuclear processes inside collimator jaw vary with energy (cross section of single-diffractive scattering increases)
- smaller beam sizes and collimator gaps
  Full collimator gaps of 1 mm or less, requiring higher precision in collimator control, setup and reproducibility.
- magnets in cleaning insertion
  warm magnets at the technological limit; shielded superconducting magnets?

Main Parameters for FLC *(TLEP)*

- Energy c.m. **91 (Z), 160 (W) , 240 (H), 350 ($\bar{t}t$) GeV**
  (energy upgrade 500-ZHH/ttH)
- Circumference ~ 100 km
- Total SR power **≤ 100 MW**
- #IPs 4
- Beam-beam tune shift / IP scaled from LEP
- Beam current 7 mA (TLEP-t) to 1400 mA (TLEP-Z)
- Horiz. geom. emittance 2-30 nm
- Vert. geom. emittance 2-60 pm
- Luminosity / IP 6×10^{35} $cm^{-2}s^{-1}$ at 91 GeV c.m.
  5×10^{34} $cm^{-2}s^{-1}$ at 240 GeV c.m.
  1×10^{34} $cm^{-2}s^{-1}$ at 350 GeV c.m.
- Top-up injection to cope with short lifetime from rad. Bhabha scattering & beamstrahlung
- Polarization at *Z* pole and *WW* threshold
- β_y^* 1 mm ~ σ_z

preliminary

Some Challenges for FLC *(TLEP)*

- Lifetime limitation by **beamstrahlung** from 120 GeV requires **robust ring optics with small β^*_y (~ 1 mm) & large momentum acceptance (≥ 2%).**
  - *Nano-beam / crab waist schemes are considered as options*
- Reaching **small vertical emittance** in large machine
- Optimization of the machine layout compatible with **high currents and larger number of bunches at Z**
  - *Number of rings and size of the RF system*
- **Polarization & precise energy calibration at *Z* pole**, with nat. polarization time ~150 h, **& at *WW*** (~5 h)
- RF w **>50% wall-plug to beam power efficiency**
- **Optics changes with energy; lepton injector chain**

lifetime limit: beamstrahlung (BS)

synchrotron radiation in the strong field of opposing beam

Note: Many theoretical beamstrahlung studies in 1980's. Example R. Blankenbecler, S.D. Drell, "A Quantum Treatment of Beamstrahlung," Phys.Rev. D36 (1987) 277

makes some $e^{\pm}$ emit significant part of their energy

& then be lost→ **limited beam lifetime**

$$\tau_{BS} \approx \frac{20\sqrt{6\pi}r_e}{n_{IP}\alpha^2}\frac{C}{c}\frac{\gamma}{\eta}u^{3/2}e^{u} \quad \text{with} \quad u = \eta\frac{\alpha}{3(r_e)^2}\frac{1}{\gamma}\frac{\sigma_z\sigma_x}{N_b}$$

V. Telnov, PRL 110 (2013) 114801

note recent new formula from BINP!

η: momentum acceptance

σ_x: horizontal beam size at IP

mitigations:

(1) large momentum acceptance η

(2) flat beams [i.e. small ε_y & large β_x^*]

→minimize $\kappa_\varepsilon=\varepsilon_y/\varepsilon_x$, $\beta_y \sim \beta_x(\varepsilon_y/\varepsilon_x)$ & respect $\beta_y \geq \sigma_z$

(3) fast top up

lifetime values (summer 2013 baseline)

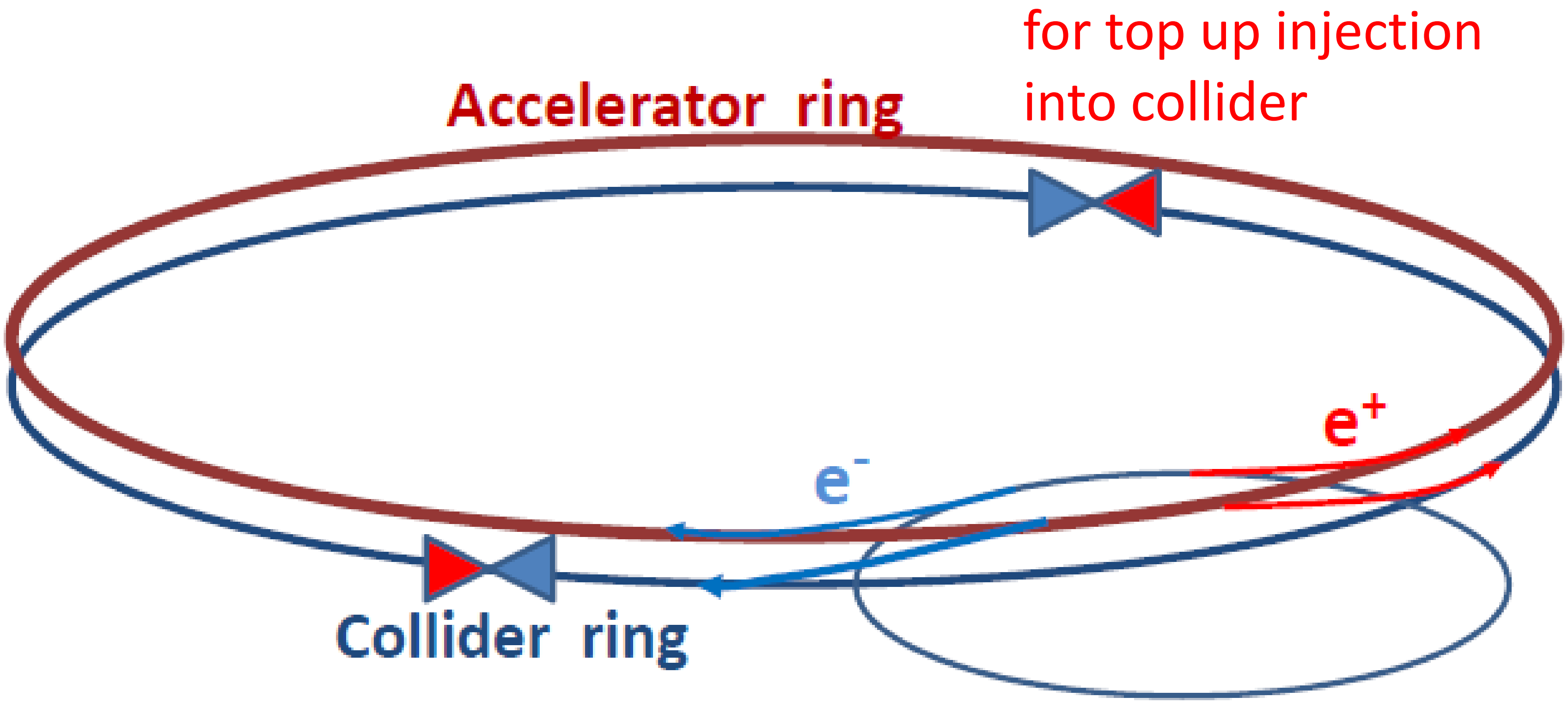
parameters	TLEP Z	TLEP W	TLEP H	TLEP t	
$E_{c.m.}$ [GeV]	**91**	**160**	**240**	**350**	
beam current [mA]	**1440**	**154**	**29.8**	**6.7**	
# bunches/beam	7500	3200	167	160	20
$\#e^{\pm}$/bunch $[10^{11}]$	4.0	1.0	3.7	0.88	7.0
ε_x, ε_y [nm]	29.2, 0.06	3.3,0.017	7.5,0.015	2, .002	
$\beta^*_{x,y}$ [mm]	500, 1	200, 1	500, 1	1000, 1	
$\sigma^*_{x,y}$[μm]	121, 0.25	26, 0.13	61, 0.12	45,.045	126,.13
$\sigma^{tot}_{z,rms}$ [mm] (w BS)	2.93	1.98	2.11	0.77	1.95
E^{SR}_{loss}/turn [GeV]	[illegible]	0.3	[illegible]	7.5	
V_{RF},tot [GV]	2	2	6	12	
$\mathcal{L}$ /IP$[10^{34}cm^{-2}s^{-1}]$	**59**	**16**	**5**	**1.3**	**1.0**
#IPs	**4**	**4**	**4**	**4**	
τ_{beam}[min] (r.Bhabha)	99	38	**24**	**21**	**26**
τ_{beam}[min] (BS,η=2%)	$>10^{25}$	$>10^{6}$	**9**	**3.5**	**0.5**

multiple beamstrahlung increases bunch length

single beamstrahlung limits beam lifeitme

based on Telnov formula

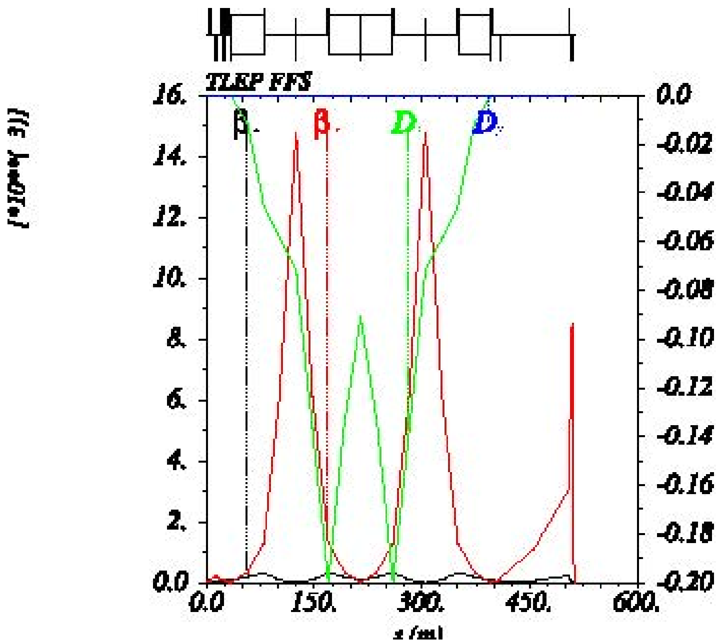
short lifetime → booster ring



A. Blondel

IR Design

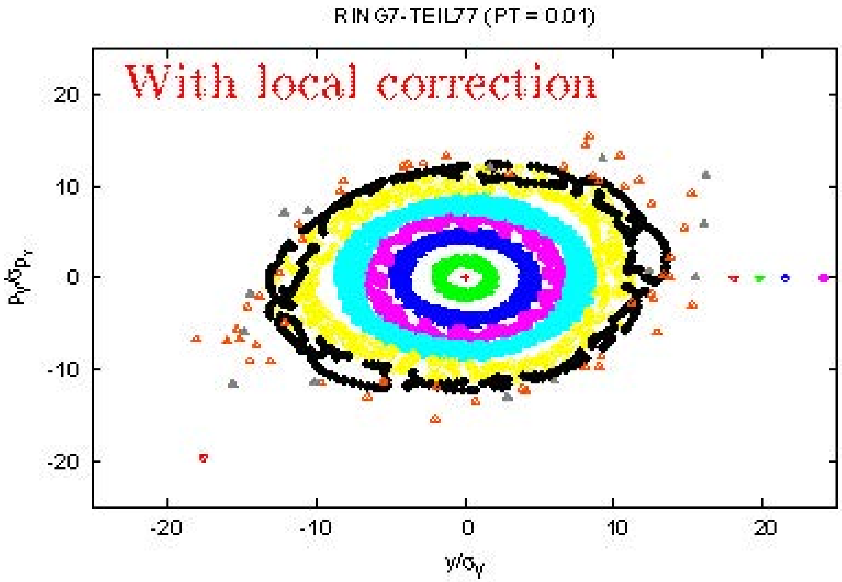
$L^* = 2.0$ m (reduced from 4 m)



H. Garcia Moralez, R. Tomas

Magnet	QF1	QD0
L [m]	1.16	2.66
k [m^{-2}]	0.195	-0.195
G [T/m]	113.6	113.6
Ap. rad. ($15\sigma_x$) [mm]	9.8	2.6
B ($15\sigma_x$) [T]	1.11	0.3

off-momentum dynamic aperture δ=1%



developing FLC/TLEP parameters …

Parameter	TLEP-Z	TLEP-W	TLEP-H	TLEP-t	LEP2
E (GeV)	45	80	120	175	104
I (mA)	1400	150	30	7	4
N_b [10^{11}]	4.0	1.0	3.7	0.88	5.8
σ_z [mm]	2.93	1.98	2.11	0.77	16..1
$\beta^*_{x/y}$ (mm)	500 / 1	200 / 1	500 / 1	1000 / 1	1500 / 50
$\varepsilon_{x,y}$(nm, pm)	30, 60	3.3, 17	7.5, 15	2, 2	40,~250
$\xi_{x,y}$/IP	.068	.086	.094	.057	.066 (*y*)
L/IP(10^{32}cm^{-2}s^{-1})	5800	1600	500	132	1.2
N_b [10^{11}]	1.5	1.0	3.0	0.88	
σ_z [mm]	1.7	1.6	1.65	0.84	
$\varepsilon_{x,y}$(nm, pm)	30, 90	4.1, 22	8.8, 19	2.3, 2.3	
$\xi_{x,y}$/IP	.029/.024	**.068, .051**	**.065, .054**	.055, .036	
L/IP(10^{32}cm^{-2}s^{-1})	**2100**	1150	350	**175**	
$\beta^*_{x/y}$ (mm)	500 / 1	500 / 1	500 / 1	500 / 1	
N_b [10^{11}]	1.0	4.0	4.7	4.0	
σ_z [mm]	5.9	9.1	8.2	6.6	
$\varepsilon_{x,y}$(nm, pm)	0.14, 1	0.44, 2	1, 2	2.1, 4.3	
$\xi_{x,y}$/IP	.032/.175	.031, .187	.029, .160	.024, .077	
L/IP(10^{32}cm^{-2}s^{-1})	**22970**	**3980**	**933**	**129**	

baseline (analytical)

baseline (simulated + opt.)

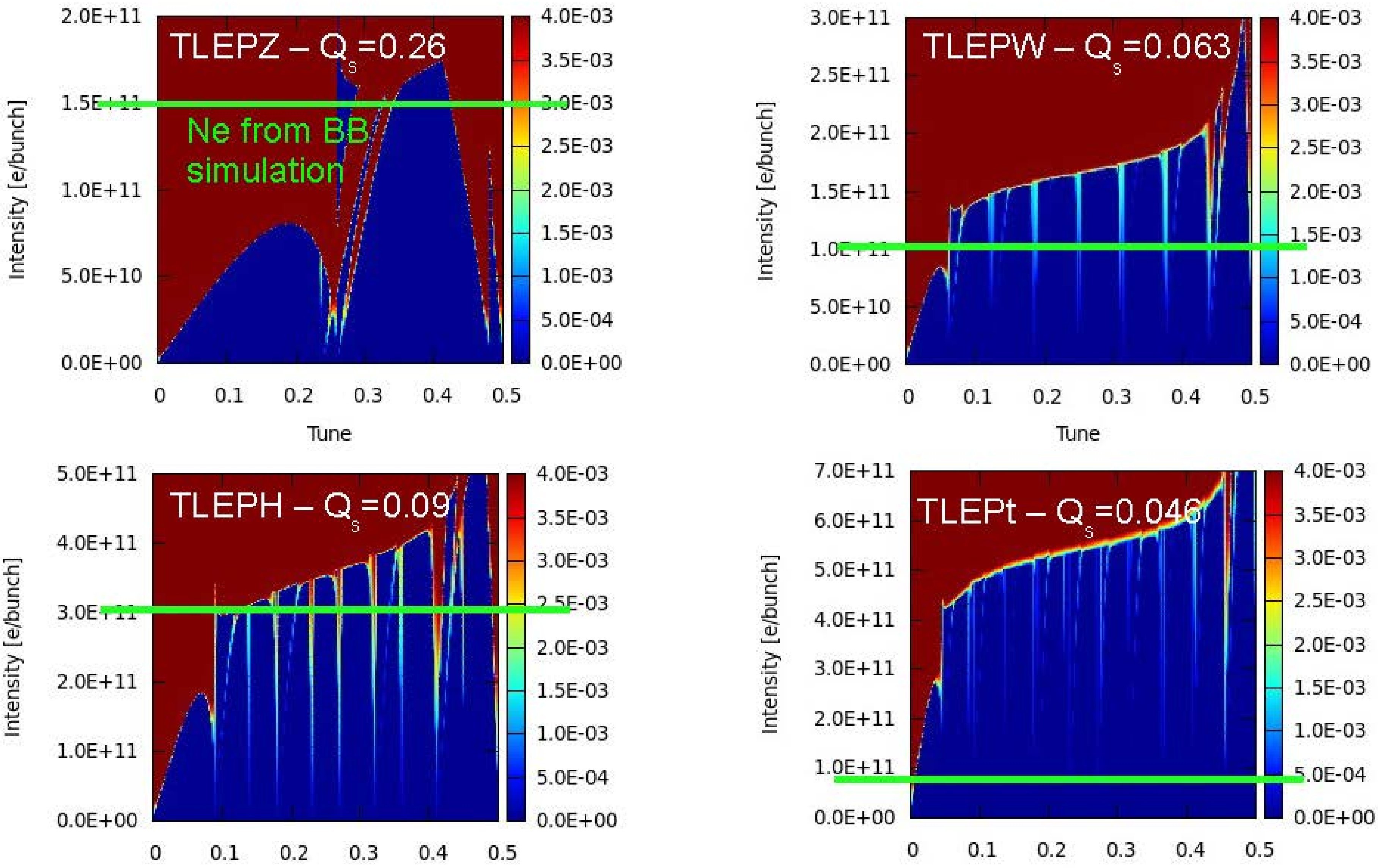
S. White, TLEP6 WS

nano-beam option

higher luminosity + much better beamstrahlung lifetime (>100 min)

A.Bogomyagkov, E.Levichev, D.Shatilov, TLEP6 WS

TMCI instability, 3 cm *y* half aperture, 5.5 m dipole



N. Mounet, S. White, TLEP6

TLEP RF - relevant parameters

Main RF parameters

Erk Jensen

- Synchrotron radiation power: 50 MW per beam
- Energy loss per turn: 7.5 GeV (at 175 GeV, t)
- Beam current up to 1.4 A (at 45 GeV, Z)
- Up to 7500 bunches of up to 4 x 10^{11} e per ring.
- CW operation w. top-up operation, injectors & booster pulsed

First look on basic frequency choice & RF system dimension

- Frequency range (200-800) MHz with 400 MHz starting point
  - **Disadvantage lower frequency**: mechanical stability, *He* amount for cooling, size …
  - **Disadvantage higher frequency**: denser HOM spectrum (multi-cell), BBU limit, larger impedance, smaller coupler dimensions
- Example scaling from LHC (per beam):
  - LHC 400 MHz → 2 MV and ~250 kW per cavity, (total 8 cavities)
  - **Lepton collider ~500 cavities 20 MV / 100 kW RF → 10 GV / 50 MW**

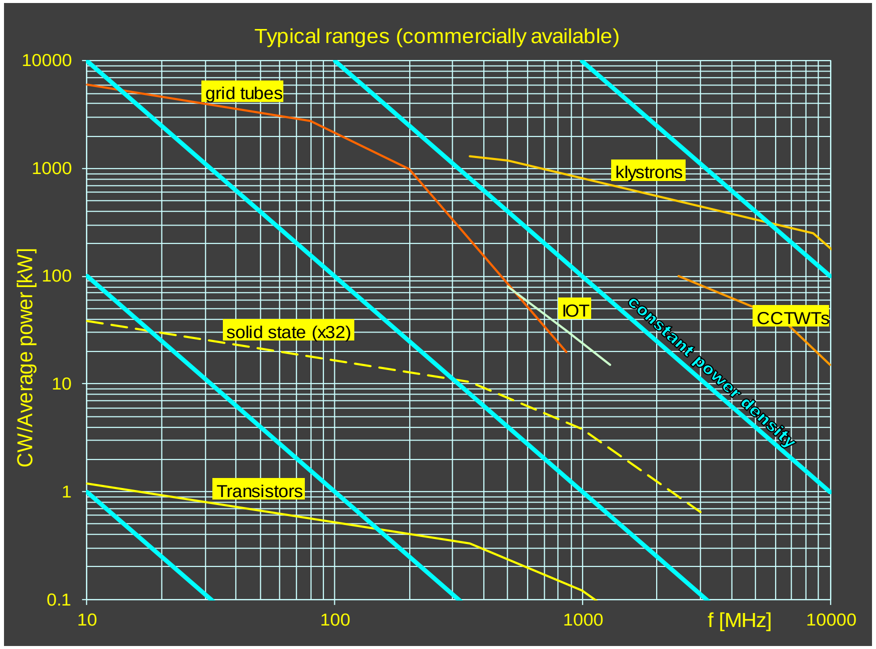
R&D issues for FLC SC RF system

- **Low cost, highly efficient RF source**
  - **IOT's, magnetrons, diacrodes, solid state ampliifers?**
- **Higher Q_0**
  - High temp furnace treatments
  - **Nb_3Sn**
  - MgB_2 or something new?
- **Improved HOM damping** (on-cell dampers?)
  - First tried on ANL crab cavity, plan to try on JLAB MEIC
  - Higher packing factor
- **Reduced cryomodule costs**
  - Cheaper materials, reduced labor

Robert Rimmer, JLAB

RF power sources – frequency scaling

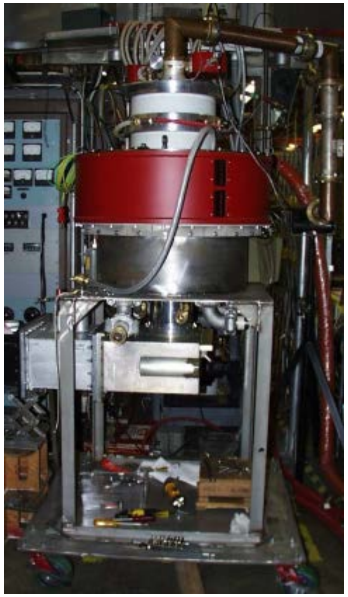
High efficiency, high power RF sources?



- **200 MHz: Tetrodes, Diacrodes; probably least expensive/MW; efficiency > 70%**
- 400 MHz, 800 MHz:
  1. Klystrons: η~65%; R&D for larger η has started
  2. **IOT**s: today limited to < 100 kW; R&D on MB IOT (1.5 MW pulsed) has started with ESS!

Thales 1MW diacrode

LEP 1.3 MW CW klystron

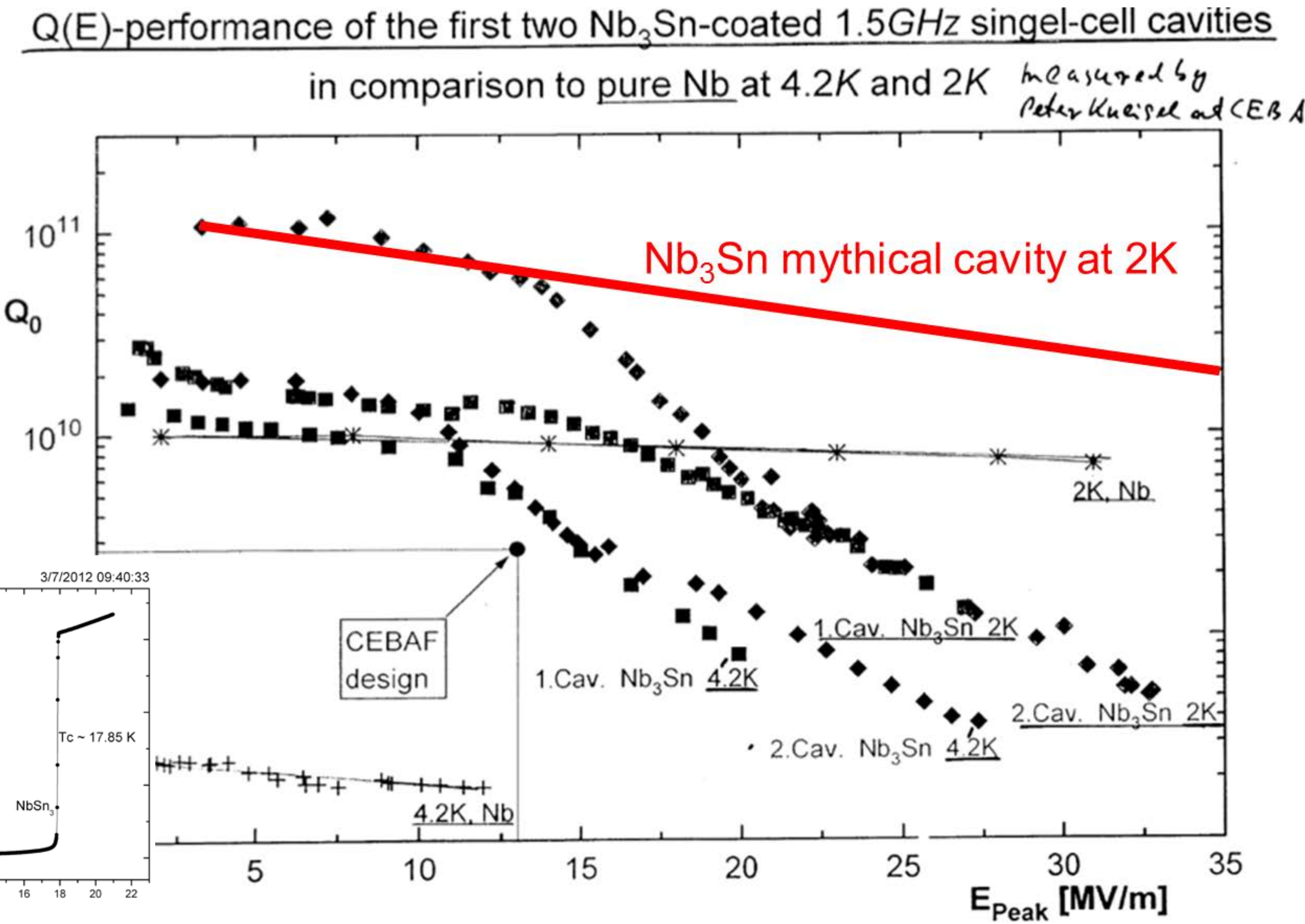


CPI MB-IOT prototype, 1MW, 700MHz

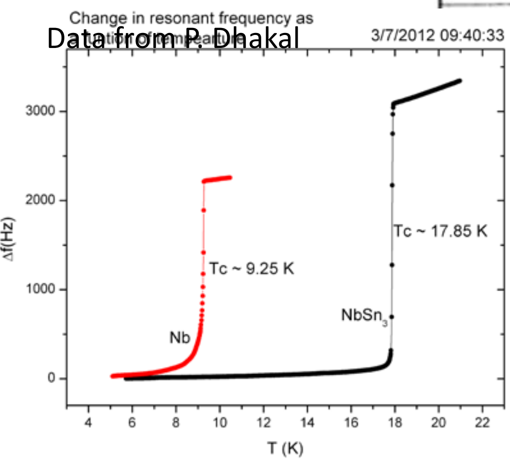
Erk Jensen

potential of *Nb₃Sn* for SRF cavities

R&D progressing at JLAB & Cornell



Data from P. Dhakal



Robert Rimmer, JLAB

Synchrotron Radiation for FLC *(TLEP)*

SR power per unit length ≈8 W/cm/beam

compare SLAC PEP-II & SPEAR3: 100 W/cm

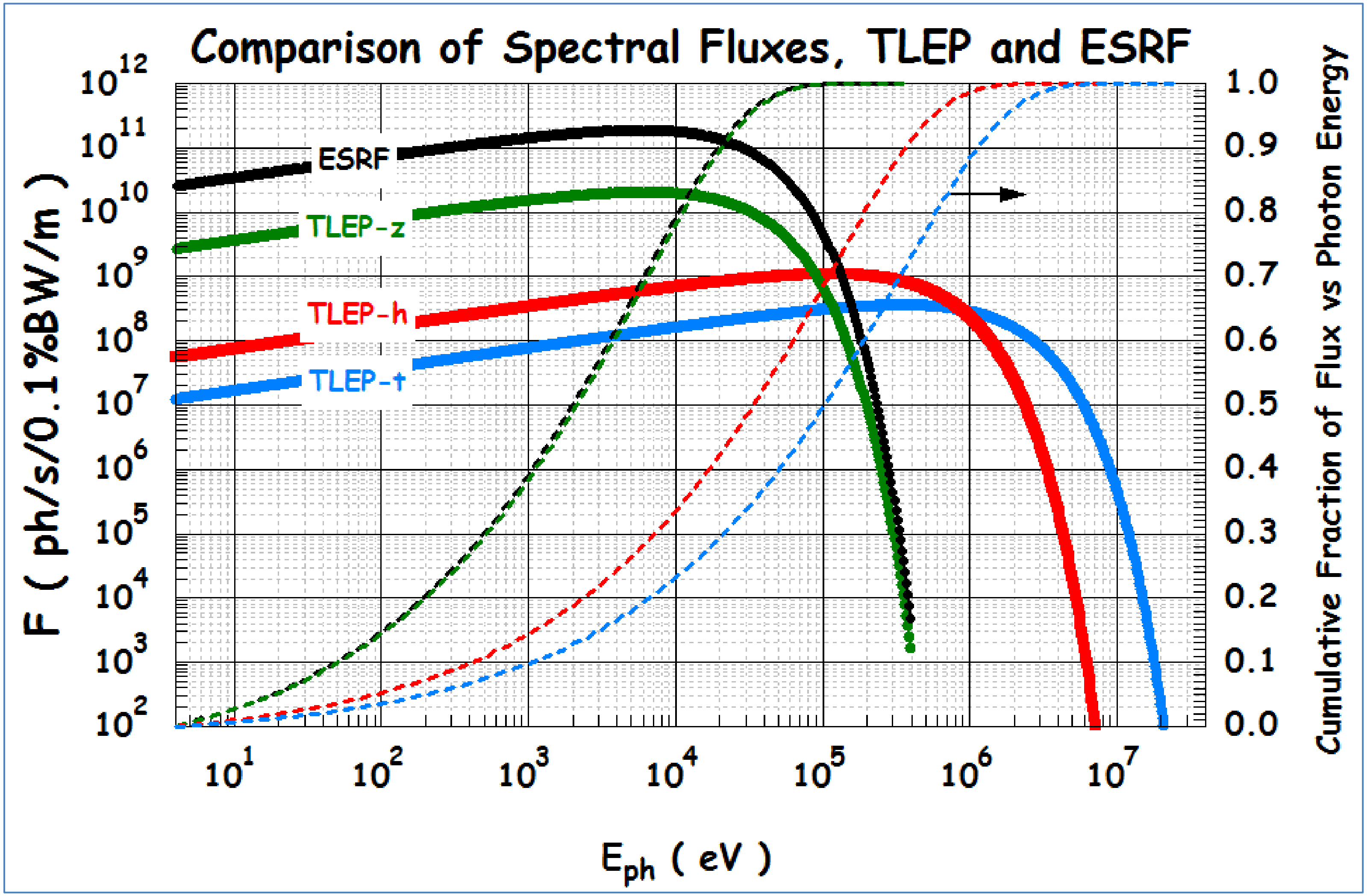
critical photon energy $E_c=(3/2)\hbar c\gamma^3/\rho\approx$

0.35 MeV for TLEP-H (240 GeV c.m.)

1.08 MeV for TLEP-t (350 GeV c.m.)

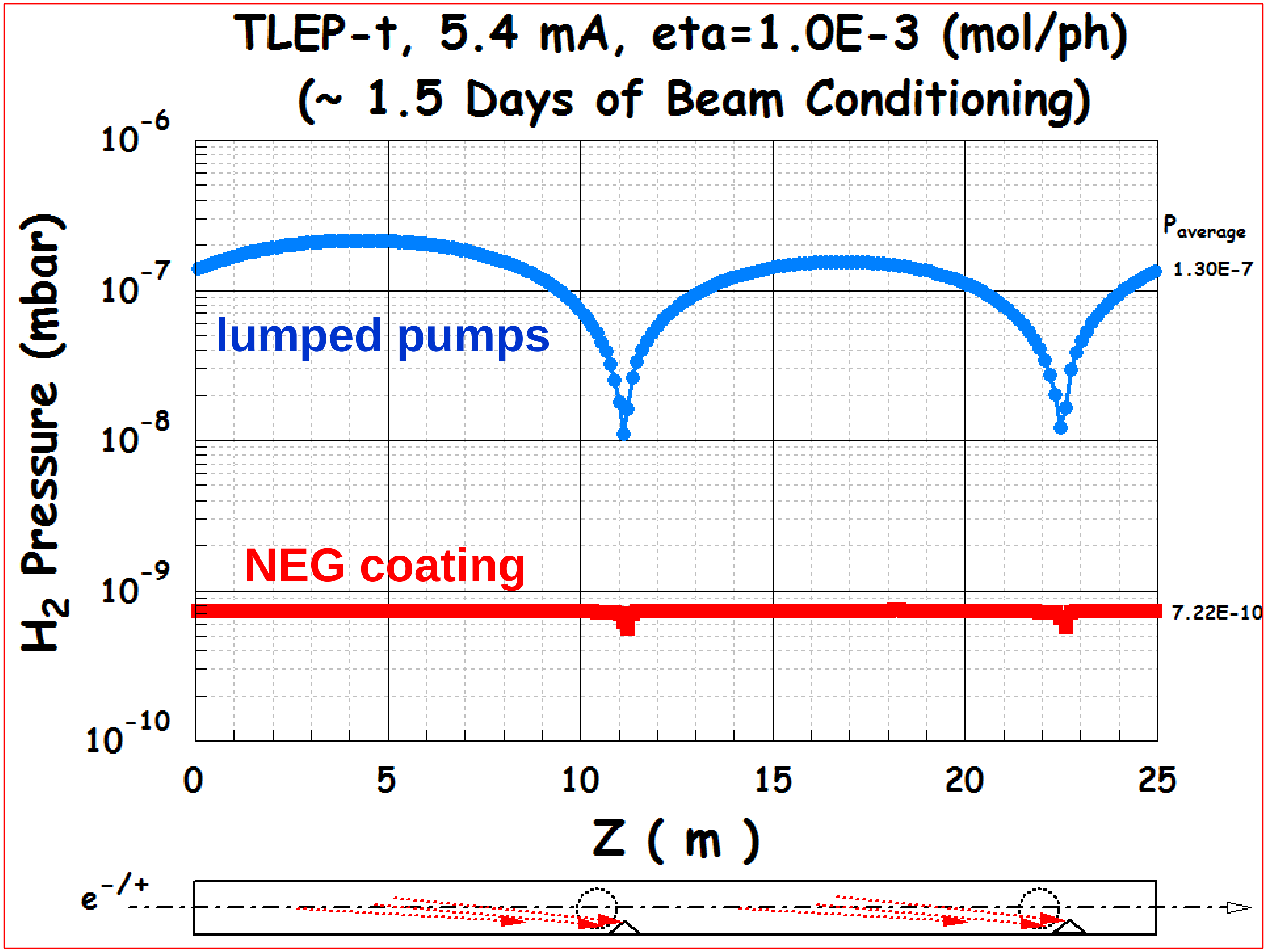
compare LEP-2: 0.82 MeV (1.58 MeV design)

TLEP SR compared with ESRF



R. Kersevan, C. Garion, TLEP6

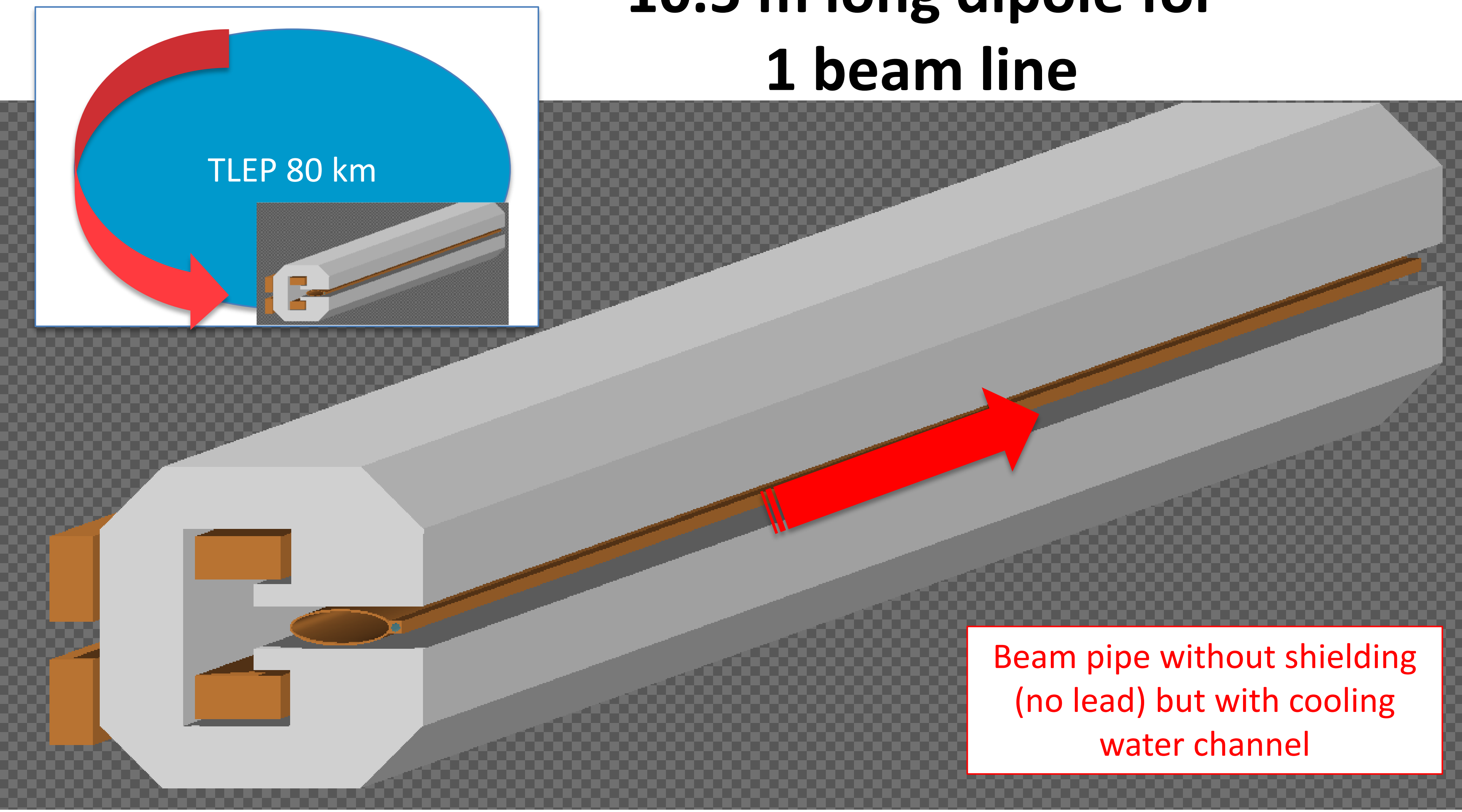
first look at vacuum system



R. Kersevan, C. Garion, TLEP6

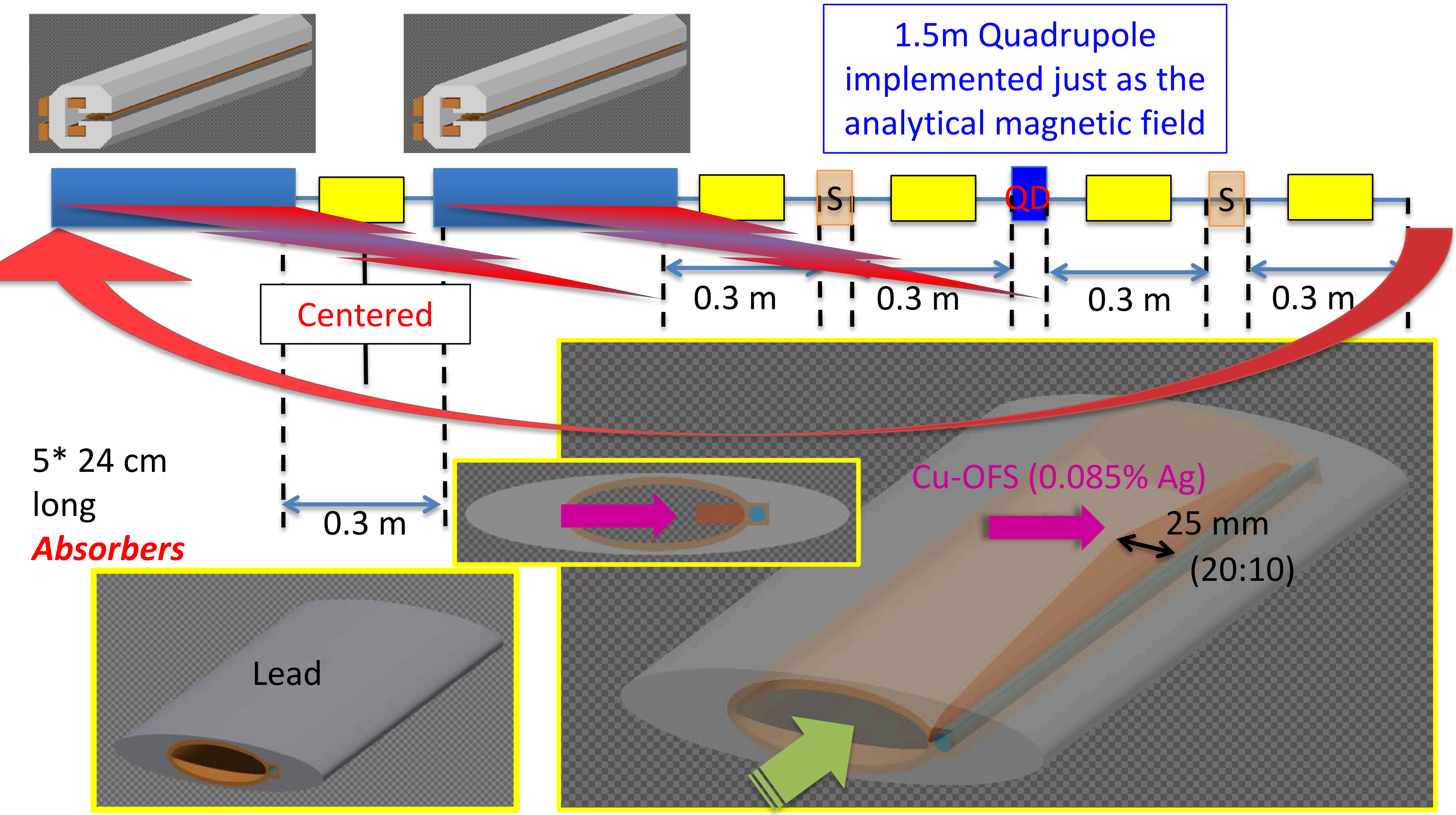
FLUKA model for radiation study

10.5 m long dipole for 1 beam line



L. Lari, TLEP6

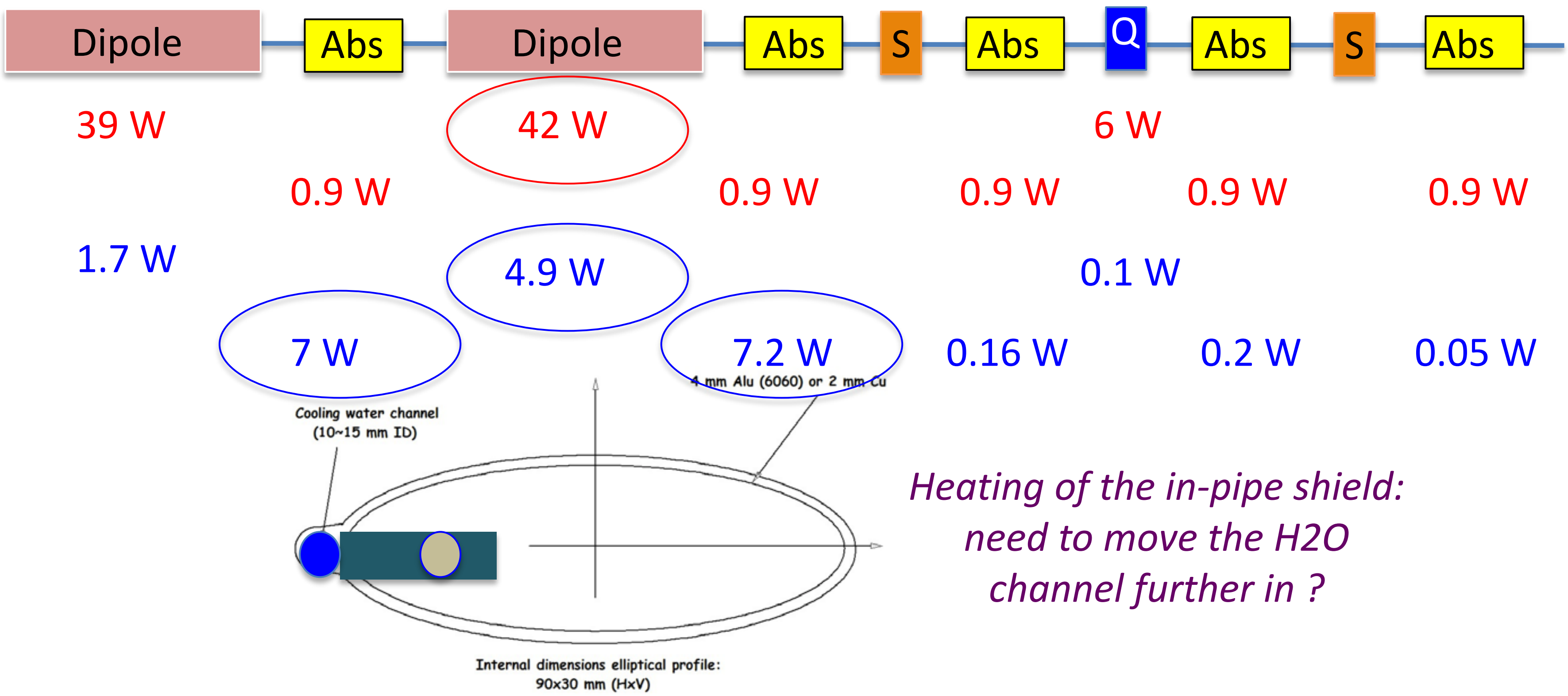
FLUKA model for radiation study



L. Lari, TLEP6

heating of cooling water

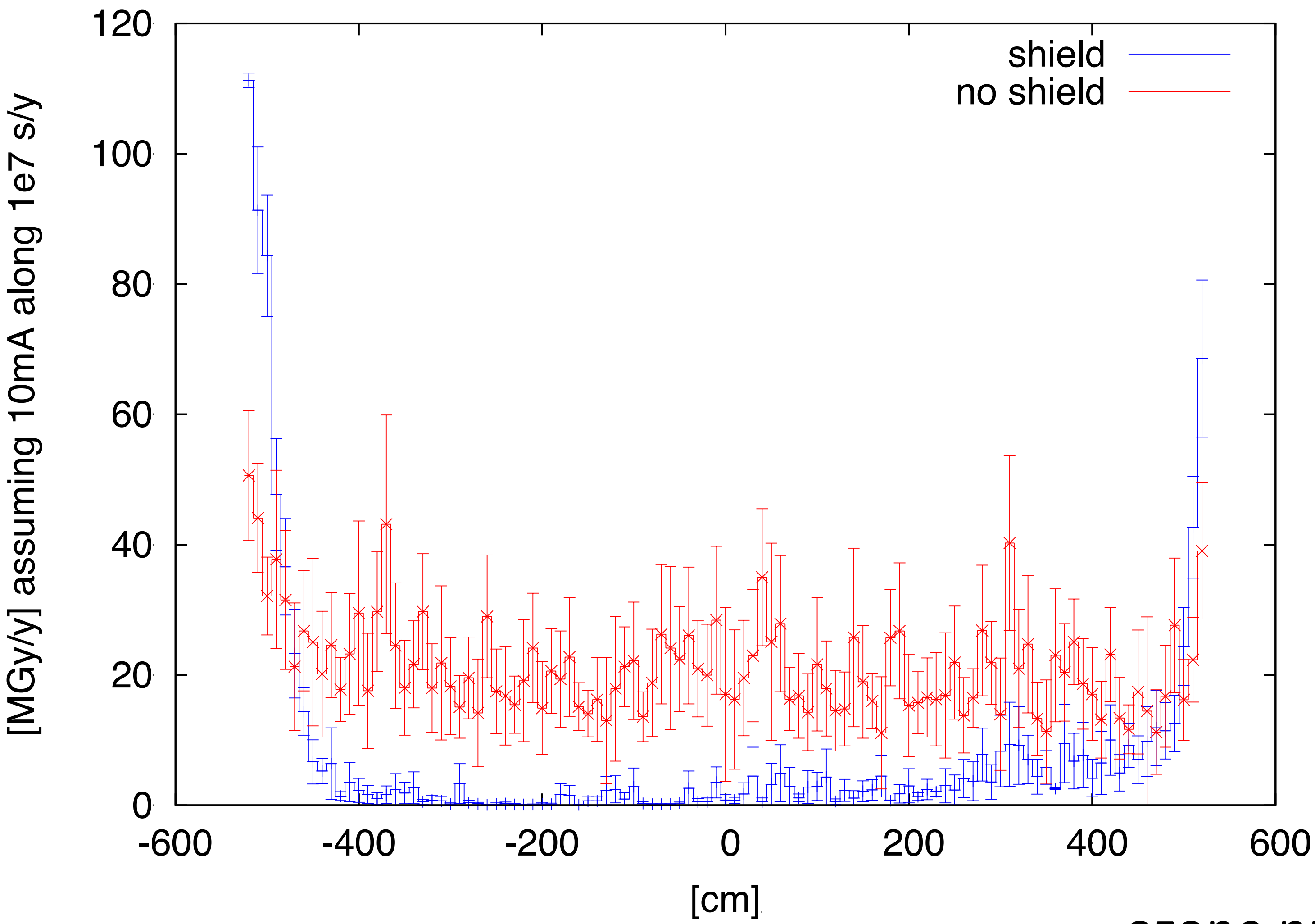
- Power in H_2O for all absorbers: 14.7 W (shield) & 4.5 W (no shield)
- Power in H_2O for all magnets: 6.7 W (shield) & 87 W (no shield)



Heating of the in-pipe shield: need to move the H2O channel further in ?

L. Lari, F. Cerutti, A. Ferrai, TLEP6

peak dose on the coils



ozone production to be looked at

L. Lari, F. Cerutti, A. Ferrai, TLEP6

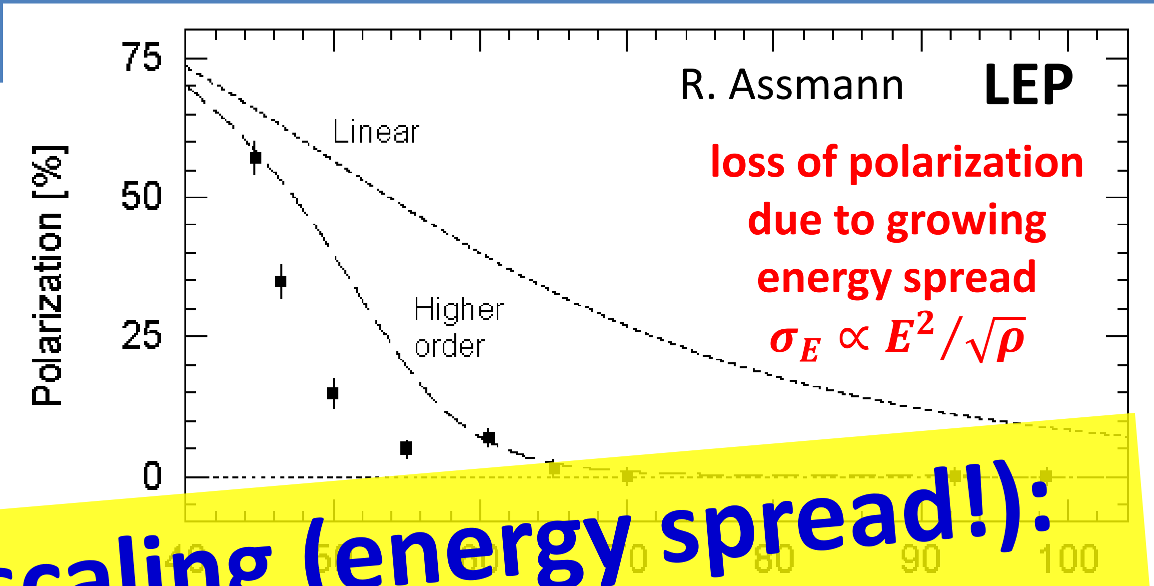
polarization

A. Blondel

LEP

observations

+ model predictions



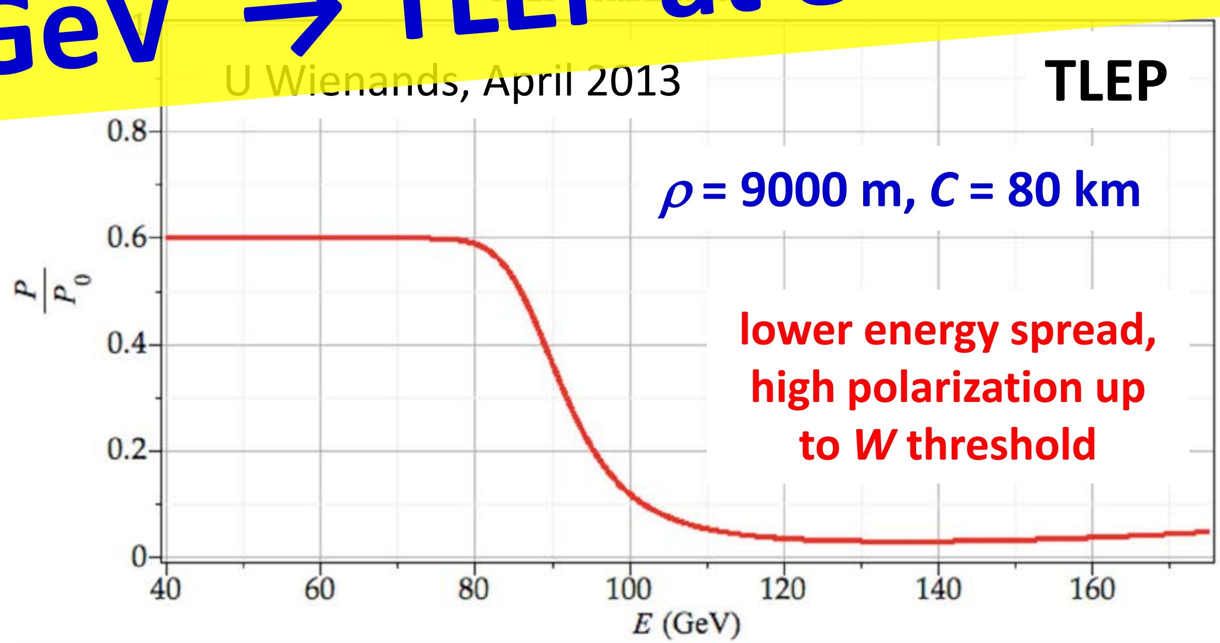
polarization scaling (energy spread!):
LEP at 61 GeV → TLEP at 81 GeV

TLEP

optimized scenario

➔ 100 keV beam energy calibration by resonant depolarization (using pilot bunches) around *Z* peak and *W* pair threshold:

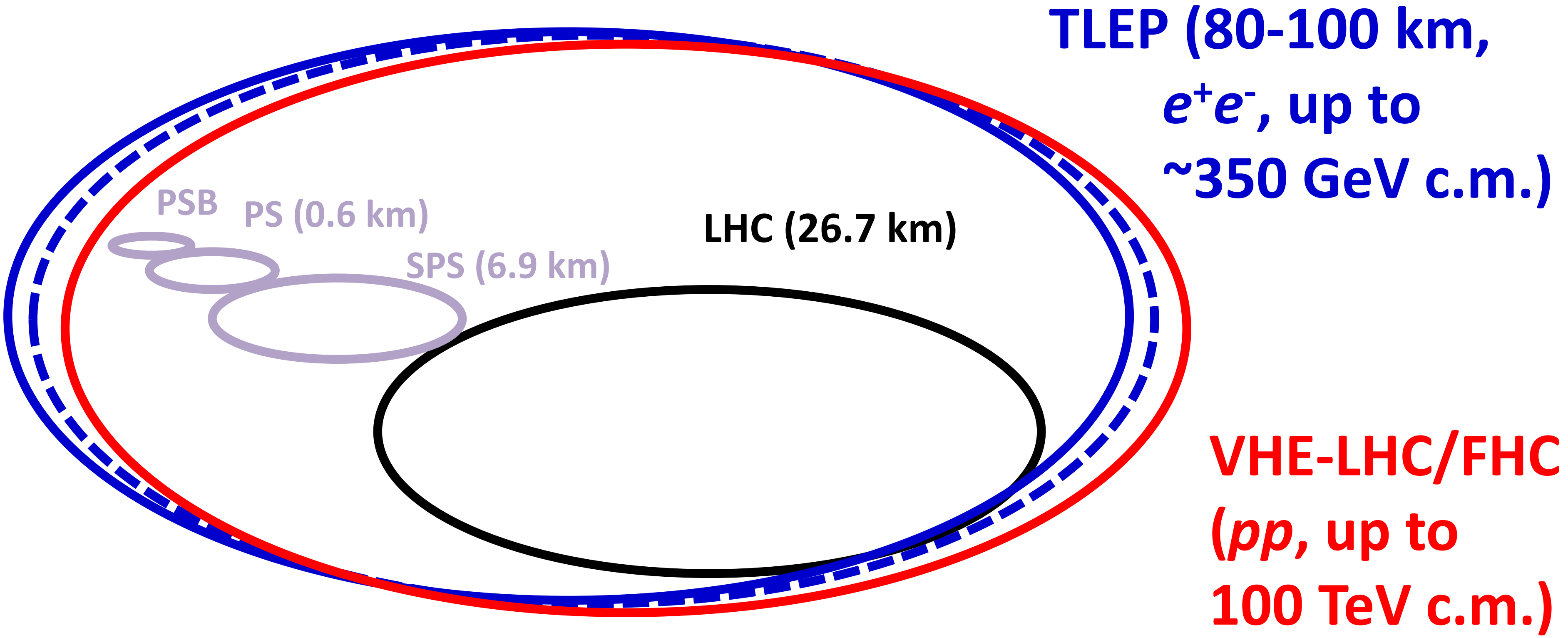
Δm_Z ~0.1 MeV, $\Delta\Gamma_Z$ ~0.1 MeV, Δm_W ~ 0.5 MeV



Main Parameters for FLHC *(VLHeC)*

• Beam energy $e^{\pm}$	60, 120, (250) GeV
• Beam energy p	50 TeV
• Spot size	set by *p (6x3 μm rms)*
• e^- current from FLC	(SR power ≤ 50 MW)
• #IPs	1
• Luminosity	2×10^{35} cm^{-2}s^{-1} at 60 GeV E_e 10^{34} cm^{-2}s^{-1} at 120 GeV E_e ~10^{33} cm^{-2}s^{-1} at 250 GeV E_e

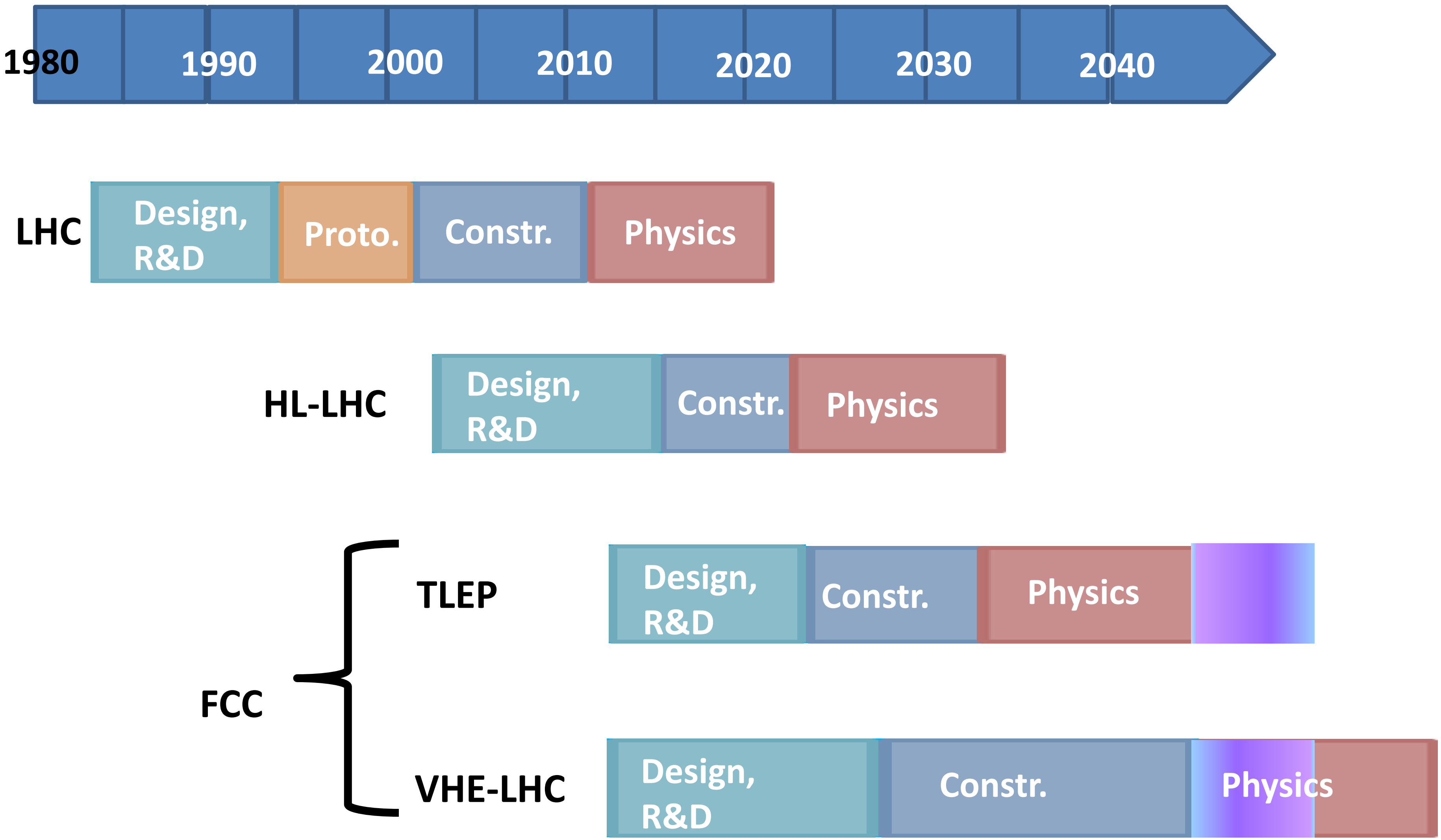
possible long-term strategy



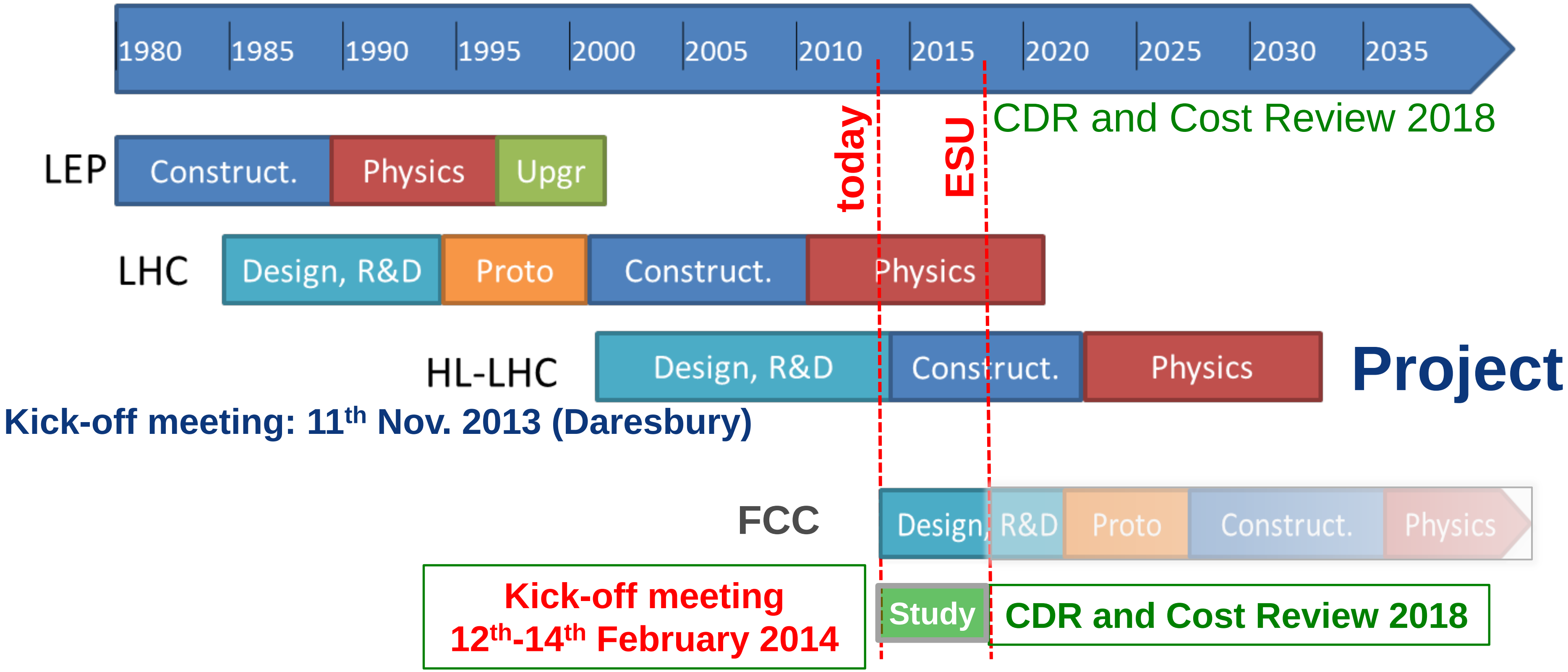
& $e^{\pm}$ **(120 GeV) – *p* (7, 16 & 50 TeV)** collisions (**[(V)HE-]TLHeC**)

≥50 years of e^+e^-, *pp*, *ep/A* physics at highest energies

a tentative time line



FCC official study milestones



FCC Summary

- CERN is undertaking an international study for the design of future circular colliders (FCC) in the 100 km range
- CDR and cost review for next ESU (2018)
- Main emphasis on hadron collider (FHC) with 100 TeV cm at the energy frontier, determining the infrastructure
- Study will also consider an e^+e^- collider (TLEP/FLC) as potential intermediate step, and look at an e-p option.
- **FCC kick-off meeting 12-15 February 2014 in Geneva University**
  - *Establish international collaborations*
  - *Define WPs and set-up study groups*
  - *International Advisory Committee (IAC)*
- **Collaboration with CepC/SppC/IHEP design study much welcome & important to make progress!**

thank you for your attention!

TLEP/FLC past events & references

A. Blondel, F. Zimmermann, *"A High Luminosity e^+e^- Collider in the LHC Tunnel to study the Higgs Boson,"* arXiv:1112.2518v1, 24.12.'11

K. Oide, *"SuperTRISTAN - A possibility of ring collider for Higgs factory,"* KEK Seminar, 13 February 2012

1st EuCARD LEP3 workshop, CERN, 18 June 2012

A. Blondel et al, *"LEP3: A High Luminosity e+e- Collider to study the Higgs Boson,"* arXiv:1208.0504, submitted to ESPG Krakow

P. Azzi et al, *"Prospective Studies for LEP3 with the CMS Detector,"* arXiv:1208.1662 (2012), submitted to ESPG Krakow

2nd EuCARD LEP3 workshop, CERN, 23 October 2012

P. Janot, *"A circular e^+e^- collider to study H(125),"* PH Seminar, CERN, 30 October 2012

ICFA Higgs Factory Workshop: Linear vs Circular, FNAL, 14-16 Nov. '12

A. Blondel, F. Zimmermann, *"Future possibilities for precise studies of the X(125) Higgs candidate,"* CERN Colloquium, 22 Nov. 2012

3rd TLEP3 Day, CERN, 10 January 2013

4th TLEP mini-workshop, CERN, 4-5 April 2013

5th TLEP mini-workshop, 25-26 July 2013, Fermilab

6th TLEP workshop (TLEP6), CERN, 16-18 Oct. 2013

http://cern.ch/accnet

http://tlep.web.cern.ch

http://cern.ch/xbeam

VHE-LHC/FHC past events & references

R. Assmann, R. Bailey, O. Brüning, O. Dominguez, G. de Rijk, J.M. Jimenez, S. Myers, L. Rossi, L. Tavian, E. Todesco, F. Zimmermann, “First Thoughts on a Higher-Energy LHC,” CERN-ATS-2010-177

E. Todesco, F. Zimmermann (eds), **“EuCARD-AccNet-EuroLumi Workshop: The High-Energy Large Hadron Collider,”** Proc**. EuCARD-AccNet workshop HE-LHC’10 , Malta, 14-16 October 2010**, arXiv:1111.7188 ; CERN Yellow Report CERN-2011-003

HiLumi LHC WP6 HE-LHC

Joint Snowmass-EuCARD/AccNet-HiLumi meeting `Frontier Capabilities for Hadron Colliders 2013,‘ CERN, 21-11 February 2013

http://hilumilhc.web.cern.ch/HiLumiLHC/activities/HE-LHC/WP16/

https://cern.ch/accnet

Additional slides

parameters	TLEP Z	TLEP W	TLEP H	TLEP t	
$E_{c.m.}$ [GeV]	**91**	**160**	**240**	**350**	
beam current [mA]	**1440**	**154**	**29.8**	**6.7**	
# bunches/beam	7500	3200	167	160	20
#$e-$/bunch [10^{11}]	4.0	1.0	3.7	0.88	7.0
ε_x, ε_y [nm]	29.2, 0.06	3.3,0.017	7.5, 0.015	2, .002	
$\beta^*_{x,y}$ [mm]	500, 1	200, 1	500, 1	1000, 1	
$\sigma^*_{x,y}$[μm]	121, 0.25	26, 0.13	61, 0.12	45,.045	126,.13
$\sigma^{tot}_{z,rms}$ [mm] (w BS)	2.93	1.98	2.11	0.77	1.95
E^{SR}_{loss}/turn [GeV]	0.03	0.3	1.7	7.5	
V_{RF},tot [GV]	2	2	6	12	
$\xi_{x,,y}$/IP	0.068	0.086	0.094	0.057	
$\mathcal{L}$ /IP[$10^{34}cm^{-2}s^{-1}$]	**59**	**16**	**5**	**1.3**	**1.0**
#IPs	**4**	**4**	**4**	**4**	
τ_{beam}[min] (rad.Bhabha)	99	38	**24**	**21**	**26**
τ_{beam}[min] (BS, η=2%)	$>10^{25}$	$>10^{6}$	**9**	**3.5**	**0.5**

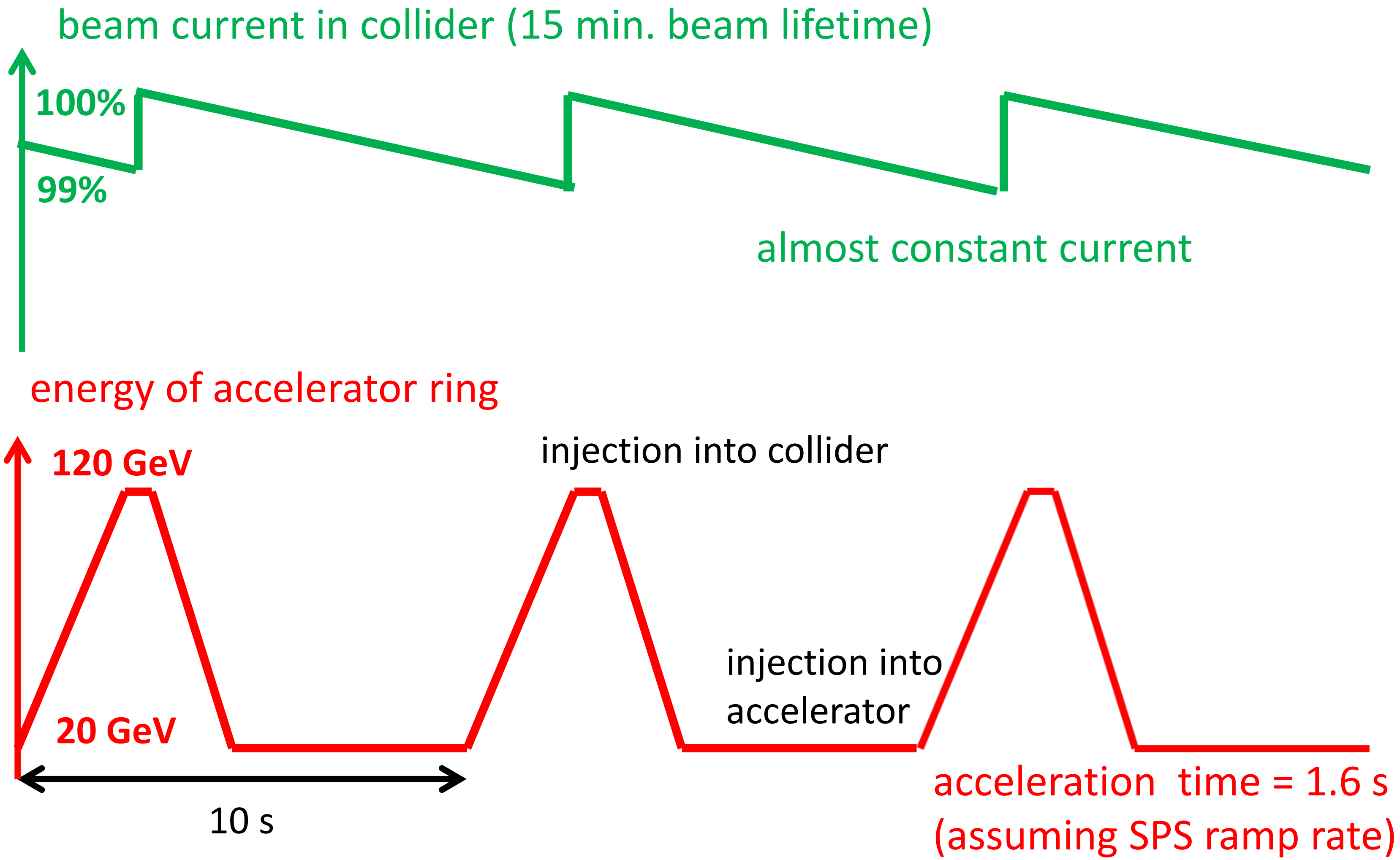
parameters	LEP2	TLEP W	TLEP H	TLEP t	
$E_{c.m.}$ [GeV]	**209**	**160**	**240**	**350**	
beam current [mA]	**4**	**154**	**29.8**	**6.7**	
# bunches/beam	4	3200	167	160	20
#$e-$/bunch [10^{11}]	5.8	1.0	3.7	0.88	7.0
ε_x, ε_y [nm]	48, 0.25	3.3,0.017	7.5, 0.015	2, .002	
$\beta^*_{x,y}$ [mm]	1500, 50	200, 1	500, 1	1000, 1	
$\sigma^*_{x,y}$[μm]	270, 3.5	26, 0.13	61, 0.12	43,.045	126,.13
$\sigma^{tot}_{z,rms}$ [mm] (w BS)	16.1	1.98	2.11	0.77	1.95
E^{SR}_{loss}/turn [GeV]	3.41	0.3	1.7	7.5	
V_{RF},tot [GV]	3.64	2	6	12	
$\xi_{x,,y}$/IP	0.066 (y)	0.086	0.094	0.057	
$\mathcal{L}$ /IP[10^{34}cm^{-2}s^{-1}]	**0.0125**	**16**	**5**	**1.3**	**1.0**
#IPs	**4**	**4**	**4**	**4**	
τ_{beam}[min] (rad.Bhabha)	363	38	**24**	**21**	**26**
τ_{beam}[min] (BS, η=2%)	>10^{35}	>10^6	**9**	**3.5**	**0.5**

com-parison with LEP2

parameters	TLEP W	TLEP H	TLEP t		ZHH&ttH
$E_{c.m.}$ [GeV]	160	240	350		**500**
beam current [mA]	154	29.8	6.7		**1.6**
# bunches/beam	3200	167	160	20	10
$\#e^{\pm}$//bunch [10^{11}]	1.0	3.7	0.88	7.0	3.3
ε_x, ε_y [nm]	3.3,0.017	7.5, 0.015	2, .002		4., 0.004
$\beta^*_{x,y}$ [mm]	200, 1	500, 1	1000, 1		1000, 1
$\sigma^*_{x,y}$[μm]	26, 0.13	61, 0.12	4[illegible],.045	126,.13	63, 0.063
$\sigma^{tot}_{z,rms}$ [mm] (w BS)	1.98	2.11	0.77	1.95	1.81
E^{SR}_{loss}/turn [GeV]	0.3	1.7	[illegible].5		**31.4**
V_{RF},tot [GV]	2	6	12		**35**
$\xi_{x,,y}$/IP	0.086	0.094	0.057		0.075
$\mathcal{L}$ /IP[10^{34}cm^{-2}s^{-1}]	16	5	1.3	1.0	**0.5**
#IPs	4	4	4		**4**
τ_{beam}[min] (rad.B)	38	24	21	26	**13**
τ_{beam}[min] (BS,η=2%**)**	>10^6	9	3.5	0.5	**~1(η=3%)**

TLEP energy upgrade?

Top-up scheme



parameters for *FHLC*

collider parameters	**$e^{\pm}$ scenarios**			**protons**
species	$e^{\pm}$	$e^{\pm}$	$e^{\pm}$	p
beam energy [GeV]	**60**	**120**	**250**	**50000**
bunch spacing [μs]	0.125	2	33	0.125 to 33
bunch intensity [10^{11}]	3.8	3.7	3.3	3.0
beam current [mA]	477	29.8	1.6	384 (max)
rms bunch length [cm]	0.25	0.21	0.18	2
rms emittance [nm]	6.0, 3.0	7.5, 3.75	4, 2	0.06, 0.03
$\beta_{x,y}$*[mm]	5.0, 2.5	4.0, 2.0	9.3, 4.5	500, 250
$\sigma_{x,y}$* [μm]	5.5, 2.7			
b-b parameter ξ	**0.13**	0.050	0.056	0.017
hourglass reduction	**0.42**	**0.36**	0.68	
CM energy [TeV]	3.5	4.9	7.1	
luminosity[10^{34}cm^{-2}s^{-1}]	**21**	**1.2**	**0.07**	

FLC (*TLEP*) luminosity formulae

$$L = \frac{f_{rev} n_b N_b^2}{4\pi \sigma_x \sigma_y} = (f_{rev} n_b N_b)\left(\frac{N_b}{\varepsilon_x}\right)\frac{1}{4\pi}\frac{1}{\sqrt{\beta_x}}\frac{1}{\sqrt{\beta_y\, \varepsilon_y/\varepsilon_x}}$$

$$(f_{rev} n_b N_b) = \frac{P_{SR}\,\rho}{8.8575 \times 10^{-5}\,\frac{\mathrm{m}}{\mathrm{GeV}^{-3}}\,E^4}$$

SR radiation power limit

$$\frac{N_b}{\varepsilon_x} \approx \frac{\xi_x 2\pi\gamma}{r_e}$$

beam-beam limit

β_x *constrained by beamstrahlung*

$\beta_y(\varepsilon_y/\varepsilon_x)$ *to be reduced as much as possible!*

lifetime limit: rad. Bhabha scattering

beam lifetime $$\frac{1}{\tau_b} = \frac{L}{I_{beam}} \sigma n_{IP} e f_{rev}$$

at beam-beam limit: $$\tau_b = \frac{2 r_e m_e}{n_{IP} \sigma f_{rev}} \frac{\beta_y}{E_b \xi_y}$$

σ for rad. Bhabha:

$$\frac{d\sigma}{dk} = \frac{4\alpha (r_e)^2}{k} \left[\frac{4}{3} - \frac{4}{3} k + k^2\right] \left[\log(4\gamma^2) + \log\frac{1-k}{k} - \frac{1}{2}\right]$$

$$\rightarrow \sigma \approx \int_{k_{\min}}^{1} \frac{d\sigma}{dk} dk \approx 0.32 \text{ barn}$$

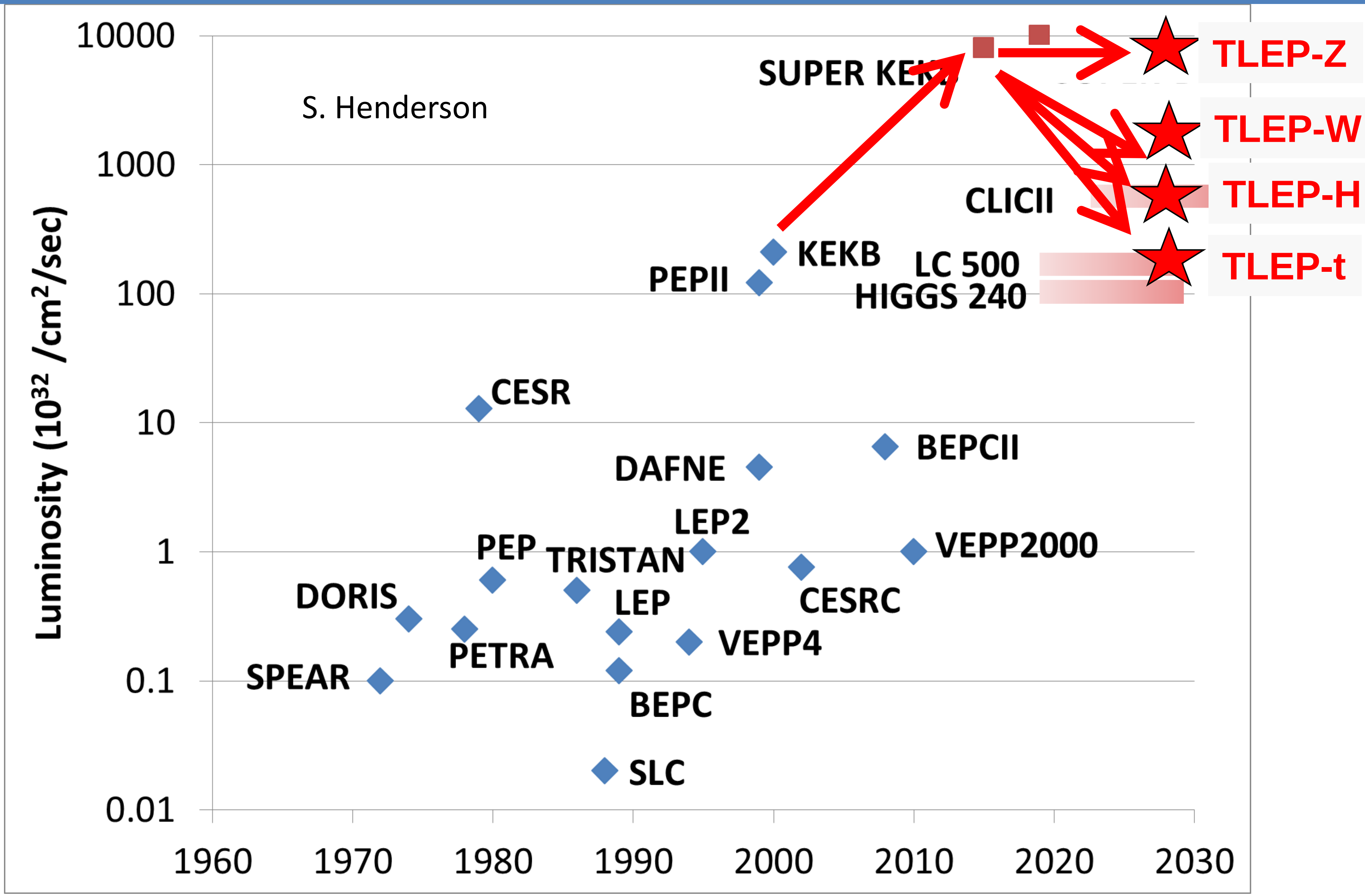
H. Burkhardt, R. Kleiss, EPAC1994

LEP2: $\tau_{\mathbf{beam,LEP2}}$ **~ 6 h** (~30% suppression: σ~0.21 barn)

TLEP **with *L*~5x10^{34} cm^{-2}s^{-1} at 4 IPs**:

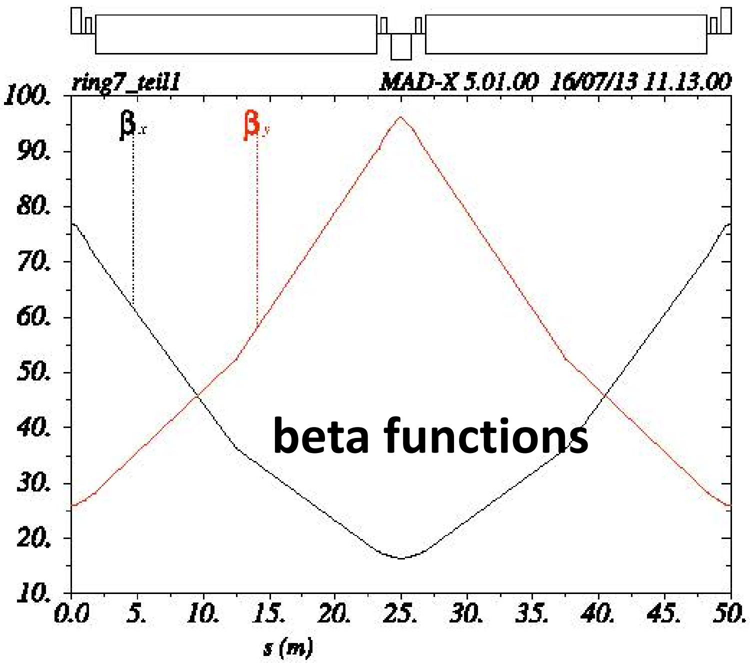
$\tau_{\mathbf{beam,TLEP}}$~21 minutes, unavoidable

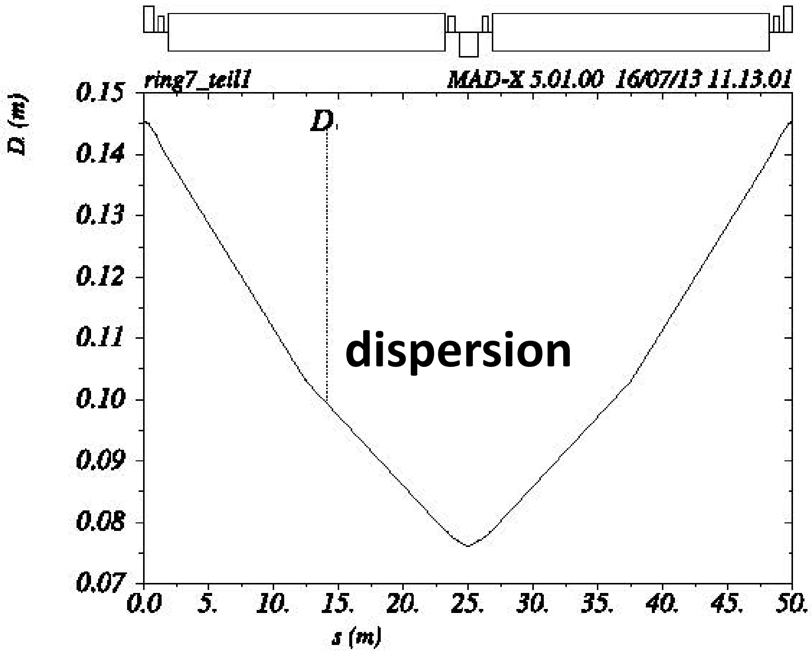
luminosity of e^+e^- colliders



optics – TLEP arc cell

Y. Cai,
B. Holzer,
H. Burkhardt





from LEP to TLEP

ρ=3100 m, L_{cell}=**79 m** ρ=9100 m (C=80 km), L_{cell}=**50 m**

ε_x=48 nm at 104.5 GeV → ε_x=1.5 nm at 175 GeV

$\varepsilon \propto \gamma^2\theta^3$: at lower beam energy increase cell length ("θ") x2 or x6!