SPS as a low emittance damping ring

Y. Papaphilippou, CERN

Thanks to F. Antoniou, R. Corsini, L. Rinolfi, H. Schmickler and F. Tecker

CLIC DR parameters

- CLIC damping rings target ultra-low emittance in all 3 dimensions for relatively high bunch charge
- Dominated by collective effects (IBS, space-charge, e-cloud, FII, CSR,…)
- Challenging technology (Variable bends, SC wigglers, Extraction kickers, RF system, Vacuum, Instrumentation, Feedback)

Parameters, Symbol [Unit]	
Number of arc cells/wigglers	90/40
Circumference, C [m]	359.4 (-18.9%)
Dipole field (max/min), B [T]	1.77/0.73
Horiz./Vert. chromaticities ξ_x/ξ_y	-162/-83
Wiggler peak field, B_w [T]	3.5
Wiggler length, L_w [m]	2
Wiggler period, λ_w [cm]	4.9
Damp. times, (τ_x, τ_y, τ_l) [ms]	(1.2, 1.2, 0.6)
Mom. compaction, α_c [10^{-4}]	1.2
Energy loss/turn, U [MeV]	5.7
Norm. horiz. emittance , $\gamma\varepsilon_x$ [nm-rad] *	500
Norm. vert. emittance, $\gamma\varepsilon_y$ [nm-rad]	5.0
Energy spread (rms), σ_δ [%]	0.13
Bunch length (rms), σ_s [mm]	1.6
Long. emittance , ε_l [keVm]	6.0
IBS factors hor./ver./long.	1.2/1.5/1.1
RF Voltage, V_{RF} [MV]	6.1
Stationary phase [°]	71

DR technology and experimental program

- **Dipoles with longitudinal gradient**
  - Demanding technology combining high-field permanent magnet material

Design study undertaken at **CIEMAT**

- **Super-conducting wigglers**
  - Demanding magnet technology combined with innovative cooling principle

Prototype built in **BINP**, and tested in **KIT-ANKA**

- **High frequency RF system**
  - 2GHz RF system in combination with high power and transient beam loading

Conceptual design at CERN, simulations in collaboration with **CalPoly**

- **Coatings, chamber design and ultra-low vacuum**
  - Electron cloud mitigation, low-impedance, fast-ion instability

Measurements at **SPS**, **CERTA**, contract with **MAXIV**

- **Kicker technology**
  - Extracted beam stability, field homogeneity, low impedance design

Stripline designed by **IFIC-Valencia** and built by **Spanish industry**, to be tested in **ALBA**, inductive adder built at **CERN**

- **Diagnostics for low emittance**
  - Profile monitors, feedback system

V-UV Profile Monitor at PSI (TIARA), collaboration with **MAXIV**

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SPS as Damping ring TF

- Use existing ring as test facility (TF) for DR R&D
- **Unconventional approach**: use SPS as DR TF
- Reviving **old ideas**, when SPS was running also as a LEP injector (one of the first proposal as DR for CLIC)
- More **recent ones**: serving as e+ DR for LHeC and pre-booster damping ring for FCCee
- **Purpose**: test components and interdependencies in similar beam conditions in the presence of synchrotron radiation (**scrubbing** with leptons?)

LHeC design report 2011

Parameter [unit]	High Rep-rate	Low Rep-rate
Energy [GeV]	10	7
Bunch population [10^9]	1.6	1.6
Bunch spacing [ns]	2.5	2.5
Number of bunches/train	9221	9221
Repetition rate [Hz]	100	10
Damping times trans./long. [ms]	2/1	20/10
Energy loss/turn [MeV]	230	16
Horizontal norm. emittance [μm]	20	100
Optics detuning factor	80	80
Dipole field [T]	1.8	1.8
Dipole length [m]	0.5	0.5
Wiggler field [T]	1.9	-
Wiggler period [cm]	5	-
Total wiggler length [m]	800	-
Dipole length [m]	0.5	0.5
Longitudinal norm. emittances [keV.m]	10	10
Momentum compaction factor	10^{-6}	10^{-6}
RF voltage [MV]	300	35
rms energy spread [%]	0.20	0.17
rms bunch length [mm]	5.2	8.8
average power [MW]	23.6	3.6

A	B	F	G	H	I
VARIABLES		*WITH WIGGLER*		Intrabeam scattering	
ETA	0.0018	brho	13.3424	ep	0.001637
VOLTS(V)	4.00E+07	wiggler deflection	0.00356	A	3.9E-06
Q VALUE	27	Bending radius	14.04463	k	0.005958
MOMENTUM COMPAC	0.0018	2*pi*rho^2	1239.369	a	0.003439
BETA (V/C)	1	F	0.005544	d	0.997034
ENERGY DPN JE	2	***Parameters With wiggler on***		lnc2a	8.492016
RADIAL DPN JX	1	Energy loss per turn	5.51E+06	Tx(sec)	1.37E+00
ENERGY(EV)	4.00E+09	Energy damping time	1.67E-02	Tz(sec)	1.23E+02
PARTICLES/BUNCH	5.00E+09	Horizontal damping time	3.34E-02		
HORIZONTAL BETA	40	Energy spread	9.11E-04		179.3655
VERTICAL BETA	40	Synchrotron Tune	0.168447		85.4419
HARMONIC NUMBER	10000	Bunch length sigma	1.07E-02		532.8773
BWIGGLER (TESLA)	0.95	Sigmasquared/beta	3.63E-10		27.19585
Pole Length	0.05	Normalised emittance	2.84E-06		179.3655
Total Wiggler Length	300	Norm long emit	7.64E-02		

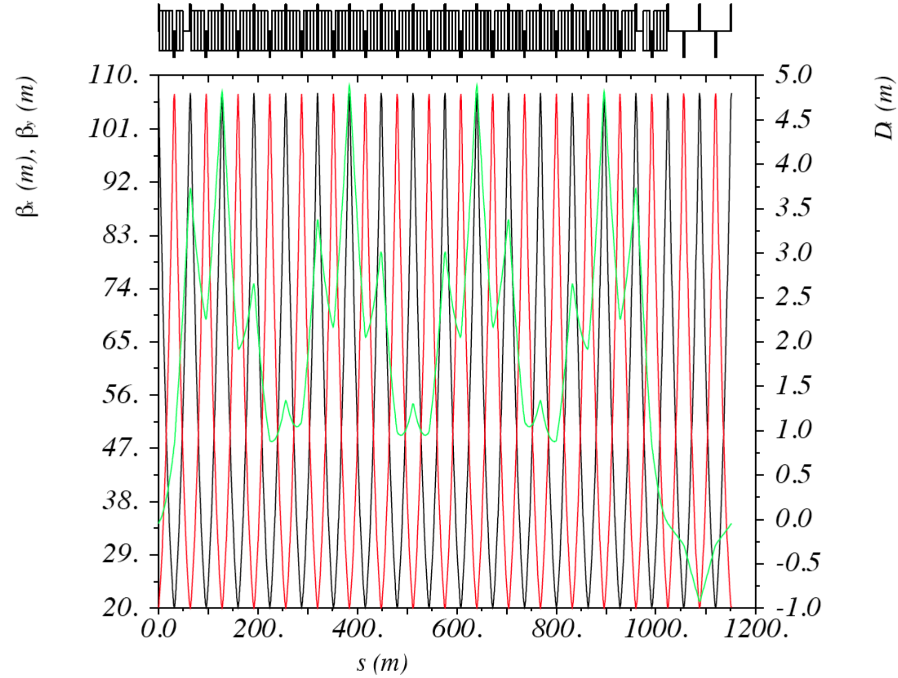
L.Evans and R.Schmidt, CLIC-Note-58, 1988

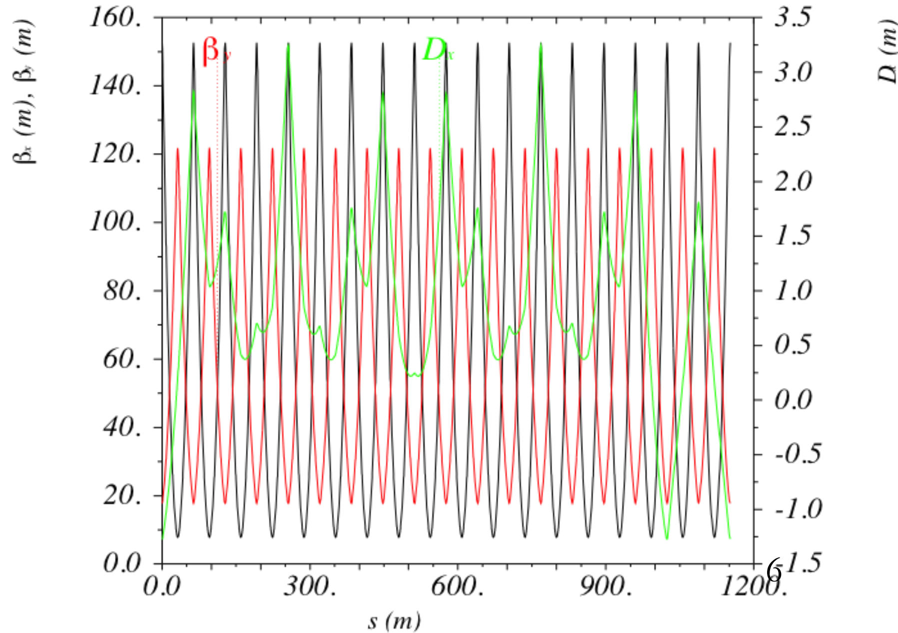
Parameter [unit]	Z		WW		ZH		tt	
Energy [GeV]	45.6		80		120		175	
Type of filling	Full	Top-up	Full	Top-up	Full	Top-up	Full	Top-up
LINAC bunches	1830	6100	1315		780		80	
LINAC repetition rate [Hz]	50							
LINAC RF freq [MHz]	2000							
LINAC bunch population [10^9]	1.65	0.06	1.50	0.30	1.54	0.40	1.62	0.87
No. of LINAC injections	5							
SPS/BR bunch spacing [MHz]	400							
SPS bunches/injection	366	1220	263		156		16	
SPS bunch population [10^{10}]	0.83	0.03	0.75	0.15	0.77	0.20	0.81	0.44
SPS duty factor	0.5		0.44		0.17		0.17	
SPS / BR bunches	1830/9150	6100/30500	1315/5260		780/780		80/80	
SPS / BR cycle time [s]	1.2 / 12		1.2 / 10.8		1.2 / 7.2		1.2 / 7.2	
Number of BR cycles	50	9	10	1	13	1	27	1
Transfer efficiency	0.8							
Total number of collider bunches	91500		5260		780		80	
Filling time (both species) [sec]	1200	216	216	21.6	187.2	14.4	388.8	14.4
Injected bunch population [10^{10}]	3.3	0.07	6.0	0.12	8.0	0.16	17.4	0.35

Y.Papaphilippou et al, IPAC 2016

SPS low emittance optics

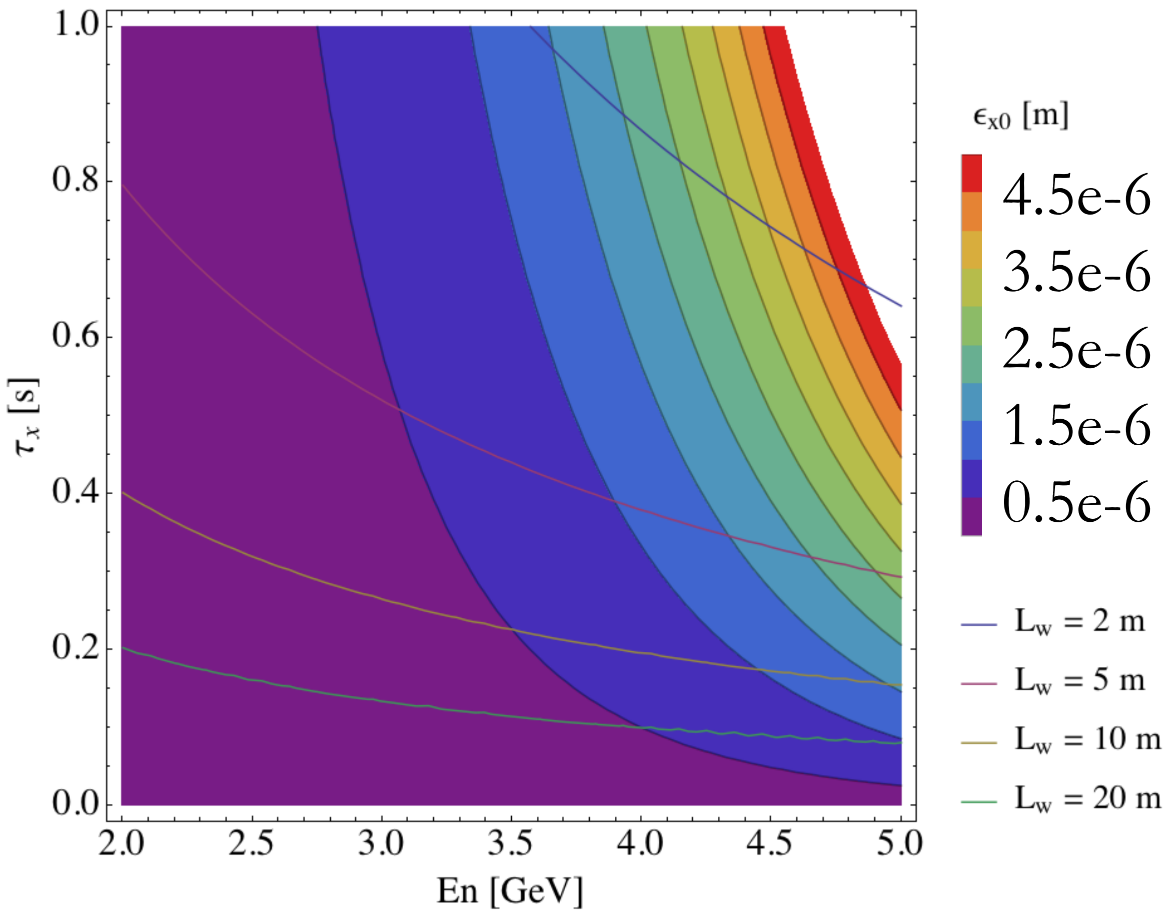
- SPS is an all **FODO** cell lattice (6 sextants), with missing dipole
- Usually tuned to 90 deg. phase advance for fixed target beams (**Q26**) and since 2012 to 67.5 deg (**Q20**) for LHC beams and considering even **Q22**
- Move horizontal phase advance to 135 (3π/4) deg. (**Q40**)
- **Normalized emittance** with nominal optics @ **3.5 GeV** of **23.5μm** drops to **9μm** (1.3nm geometrical)
  - Mainly due to dispersion decrease
  - Almost the normalized emittance of ILC damping rings
- **Damping times** of **9s**
- Natural chromaticities of -71,-39 (from -20,-27)





Emittance

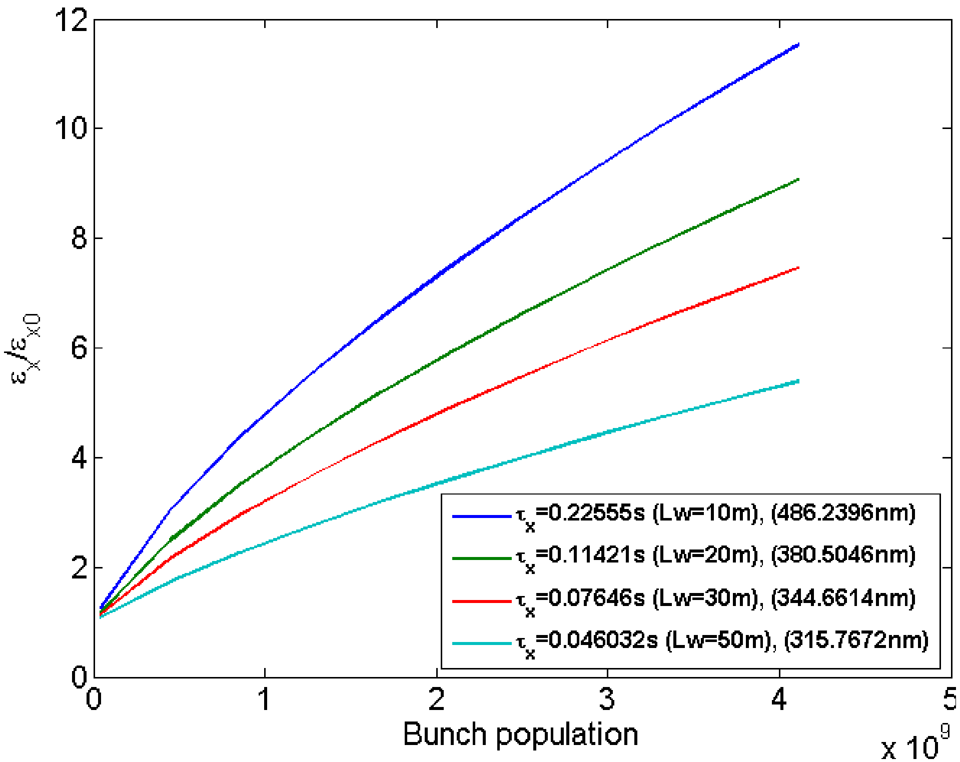
- **Energy** and **damping time** can be parameterised with equilibrium emittance, for **different wiggler lengths**
- **Ultra-low emittance** achieved in energy range of 2 to 5 GeV



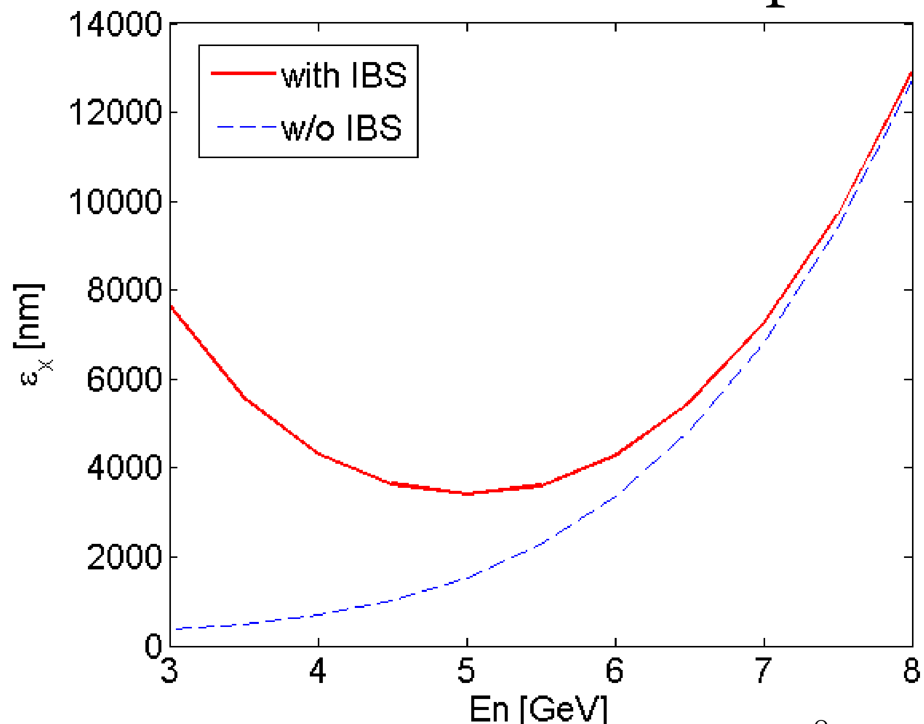
- For reaching emittances below the CLIC target of **500nm** (i.e. from 130 to 50pm geometrical in that energy range), a **few meters** of **damping wigglers** should be used

Intrabeam Scattering

- Scaling of the **blow-up** due to IBS in the horizontal plane with the bunch population, @ **3.5GeV** for different total wiggler length (thus damping times and zero current emittance)



- For a total wiggler length of 10 m and for the CLIC bunch current **Nb=4.1e9, minimum** at around **5 GeV** but still a factor of 2 blow up

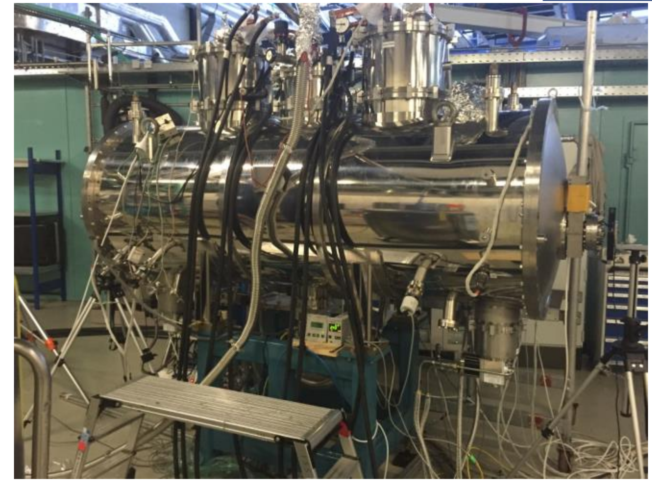


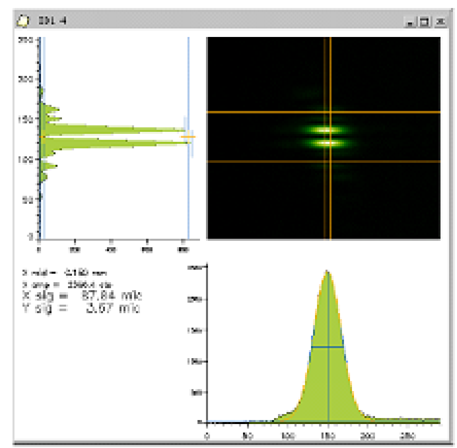
Tentative e-SPS parameters

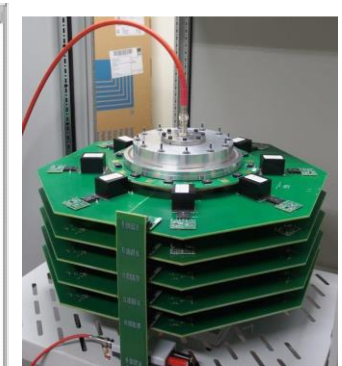
Parameter [Unit]	Lw=0m	Lw=2m	Lw=10m	Lw=2m	Lw=10m
Energy [GeV]	3.5	2.6	**3.5**	5	6.8
Hor. Norm. emit. [nm]	8800	**480**		5600	
Damping time (x,y) [sec]	9	1.46	**0.22**	0.64	**0.11**
Bunch length [mm]	**3.6**	11.5	**16.1**	20.5	32.5
Energy spread [%]	0.011	0.13	**0.15**	0.16	0.20
Energy loss/turn [MeV]	0.02	0.08	**0.72**	0.36	2.8
Bunches/pulse	**<=4620**				
Bunch spacing [ns]	**5**				
Repetition rate [Hz]	**0.83**				

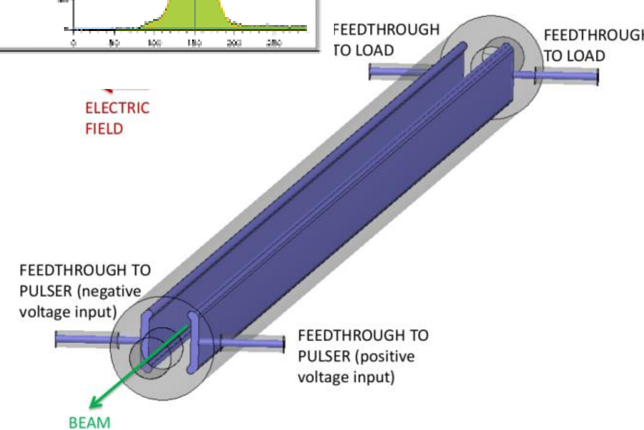
Potential experimental tests

- Super-conducting wiggler tests
- Kicker tests
- Vacuum tests (coatings)
- Instrumentation
  - Beam profile monitors (synchrotron light), Halo monitoring, BPMs
- Feedback
  - Bunch-by-bunch, turn-by-turn (LARP)
- RF system
  - 800MHz cavity (short bunches)
- Beam dynamics experiments
  - Optics, non-linear dynamics, IBS, instabilities, e-cloud (for e+), ions (for e-)



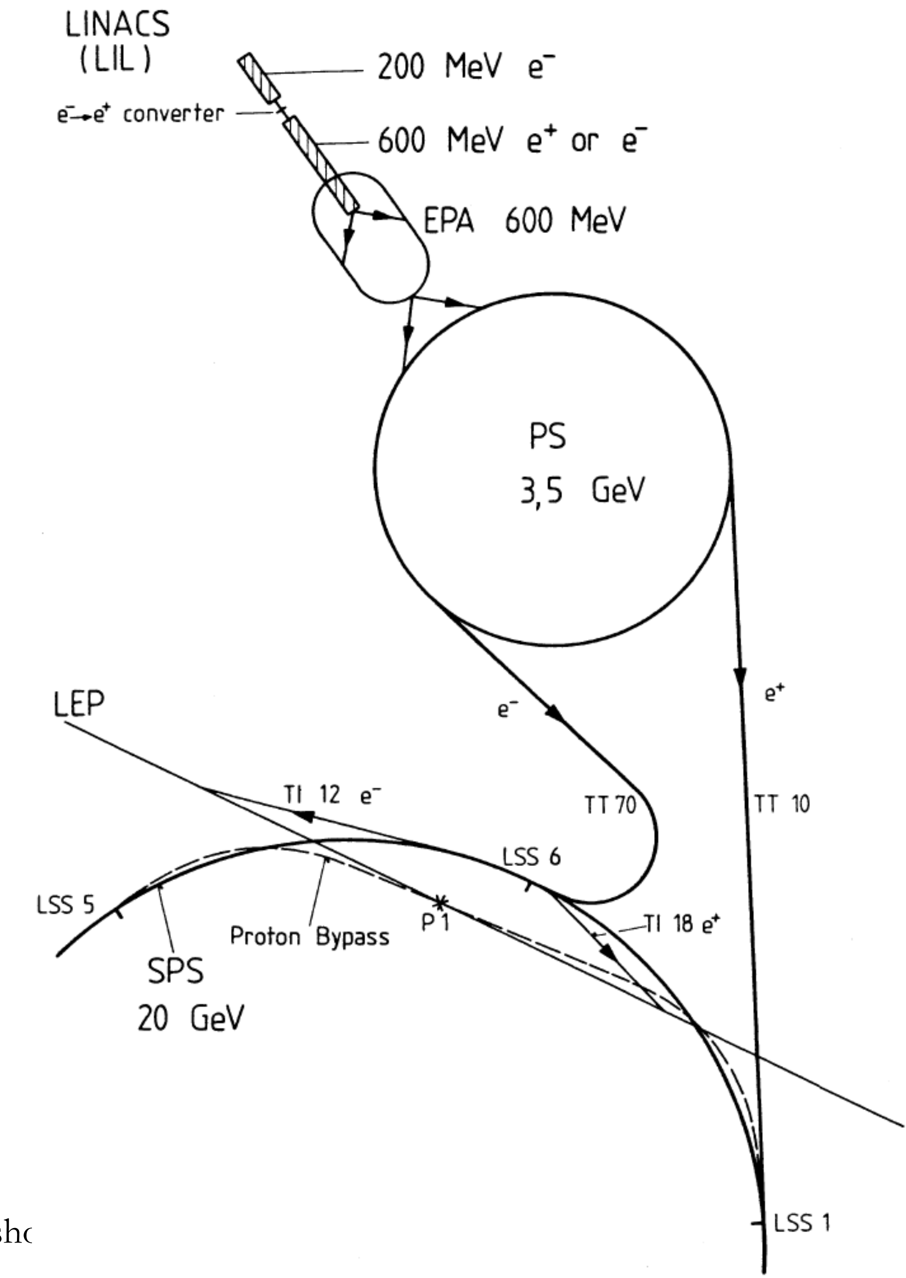






EP Injector complex

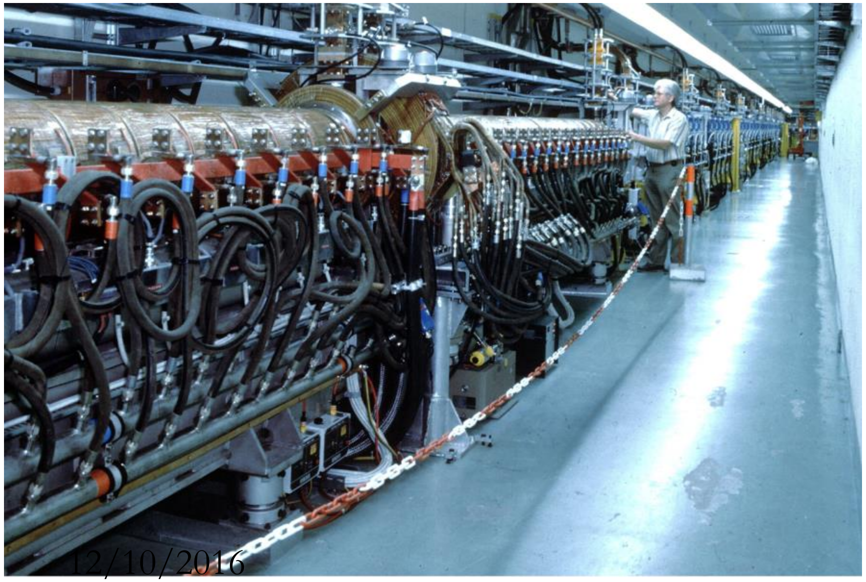
- Need to **revive** a **"LEP-like" injector complex**
- Pre-injector includes and e/p linac at a few hundreds MeV (LIL at LEP), and accumulator (EPA for LEP)
- It should be transferred through PS to SPS
- **Transfer line** for positrons exists (**TT10**) but for **electrons** (TT70) completely **dismantled**



LPI – LEP Pre-Injector

F. Tecker, CLIC workshop 2014

- **500 MeV e-/e+** into the PS
- **EPA storage ring** had 1/5 of PS circumference (40πm=125.66m) => multi-bunch transfer to PS
- 19.1 MHz RF system, 50 kW, h=8
- **e+** production by **200 MeV linac** + **W-target**

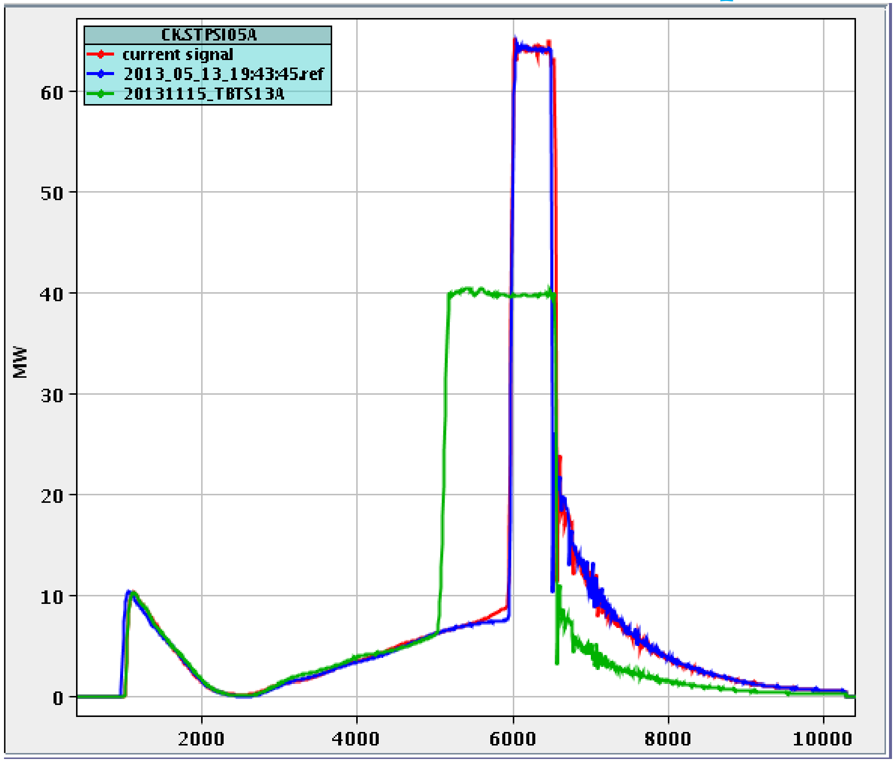


CTF3 Linac Beam Energy

- Present end-of-linac energy ~**120 MeV** for full beam-loading
- Short beam pulse => change RF compression

F. Tecker, CLIC workshop 2014

- Length ~ cavity fill time (100ns) + beam
- Gain of >2 in power
- √2 in energy => 170 MeV
- Short pulse => ~ no loading
- **final energy: ~ 340 MeV**
- +2 structures on girder 14: ~ 370 MeV

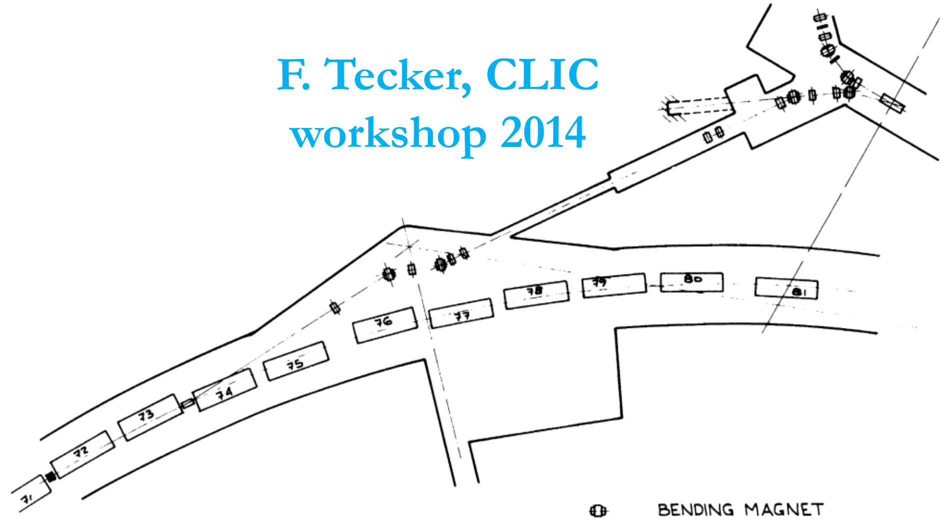


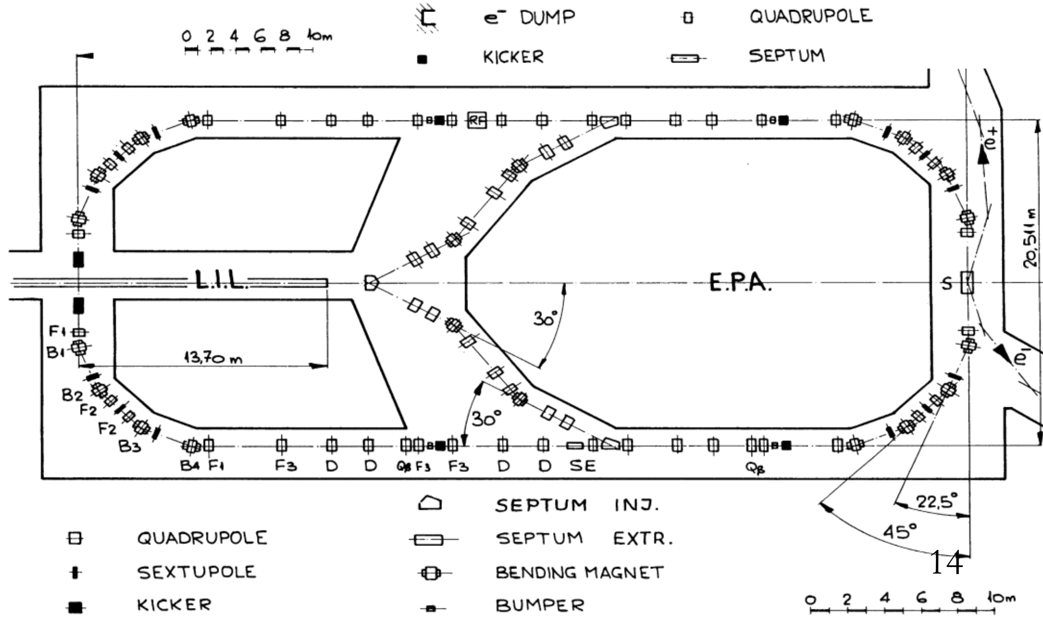
- **Magnets** and **power convertors** for TL1 and combiner ring are **compatible** with this energy

Linac bunch structure and transfer to the PS

- CTF3 linac:
  - Thermionic gun with pulse length < 1.3µs
  - 1.5 GHz sub-harmonic bunching, bunch charge **2.33nC**
  - 3 GHz acceleration (333ps period)
- needed for SPS:
  - bunch charge <0.8nC
  - single bunch or bunch spacing 5ns, 25ns (40MHz)
- => use laser RF or DC gun produce right time structure
- Replace CR wiggler by extraction septum
- Rebuild ~40-50m long extraction line
  - There were 4 bends and 9 quadrupoles (had energy sprea acceptance: 0.6 10^{-3})

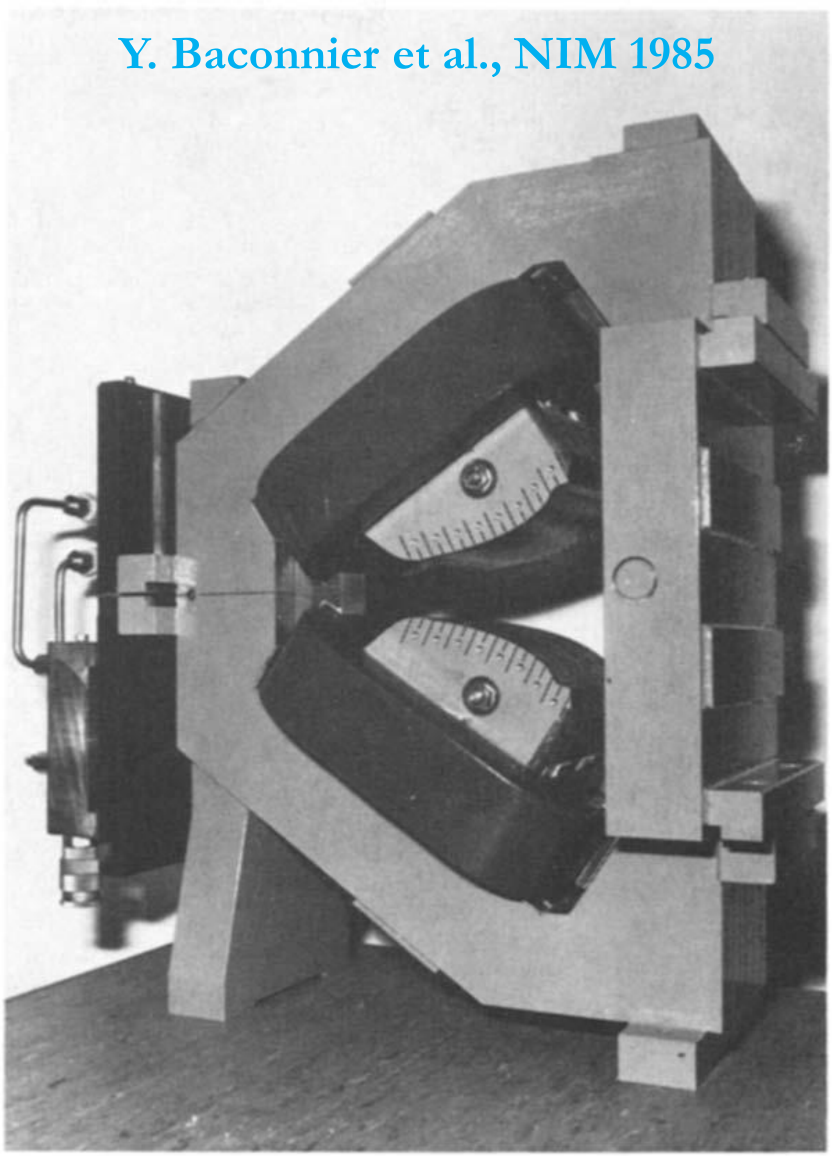
F. Tecker, CLIC workshop 2014





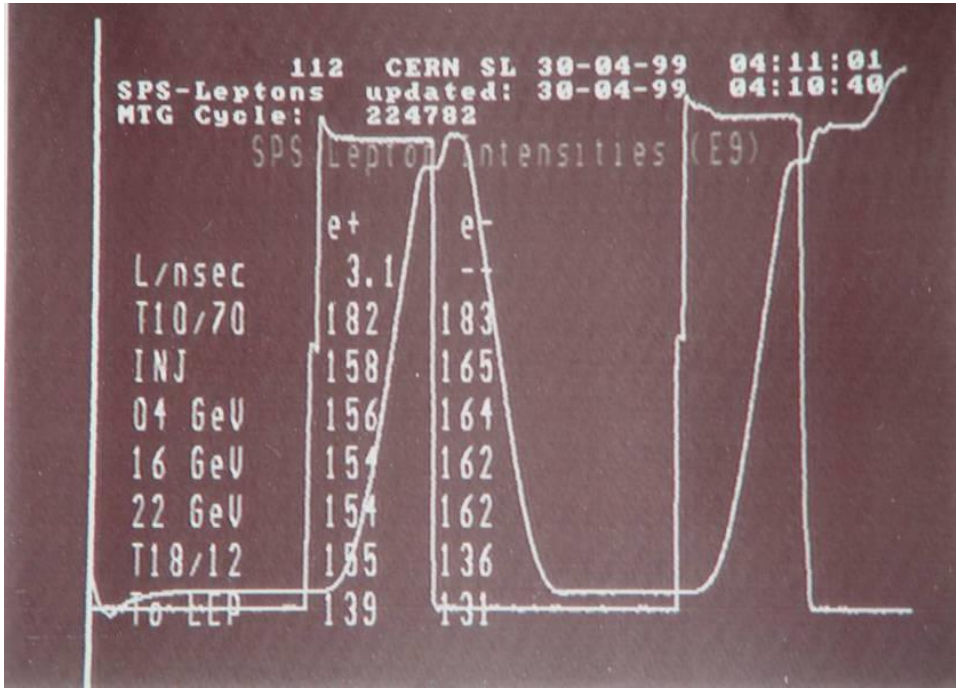
Leptons through PS to SPS

- PS: from 400 MeV -> 3.5 GeV
  - had 114 MHz RF system (2*500kV, 2*50kW)
    (taken out 2001)
  - had 2 Robinson wigglers controlling damping partition (antidamping in H-plane)
- RF had special ‘expansion’ of the long. Emittance
- Energy acceptance: E=400 MeV, $\eta=-\alpha=-0.027$
  - Present 200 MHz system, h=420, 8*30kV => $\Delta E/E < 5.7\ 10^{-3}$
  - 40/80 MHz systems have 2*/3*300kV, respectively => $\Delta E/E$ < 2% / 1.75%
  - 40/80 MHz do not match with the CR rev. frequency
- Filling the PS with CTF3 @50Hz, then ramp @3.5 GeV(2-7 *1.2), fill the SPS in 2-3min
- Full parameter list to be worked out…


Y. Baconnier et al., NIM 1985

SPS as LEP Injector

P. Collier – Academic Training 2005



- LEP filling interleaved with FT proton operation
  - Initially supercycle of **14.4s** and later **12s**
- 4 cycles with 4 bunches ($2e^+$, $2e^-$) evolved to 2 cycles with 8 bunches (~$\mathbf{2.5\times10^{10}}$ p/b)
- Injection energy of 3.5GeV
- Energy to LEP: 18 → 20 → 22 GeV
- Lots of RF for leptons (200MHz SWC, 100MHz SWC, 352MHz SC), all **dismantled** for impedance reduction
- 2 Extractions in Point 6 towards LEP
- Flux of $\mathbf{1.7\times10^{11}}$ p/s for each cycle

Further studies

- Transfer-line and injection/extraction elements
- Issues with positrons
  - Existing transfer line but new production scheme
  - Investigate polarity reversal for accomodating electrons through the existing complex (PS-TT10-SPS)
- Complete parameter set for PS and SPS including DA and coupling simulations, collective effects and synchrotron radiation absorption
- Test the new optics in the SPS with protons at low energy
- Establish synergies with different projects (CLIC, FCC, AWAKE,…)
- Cost estimate…

Thank you