Lepton injector options

Yannis PAPAPHILIPPOU, CERN

With contributions of

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Outline

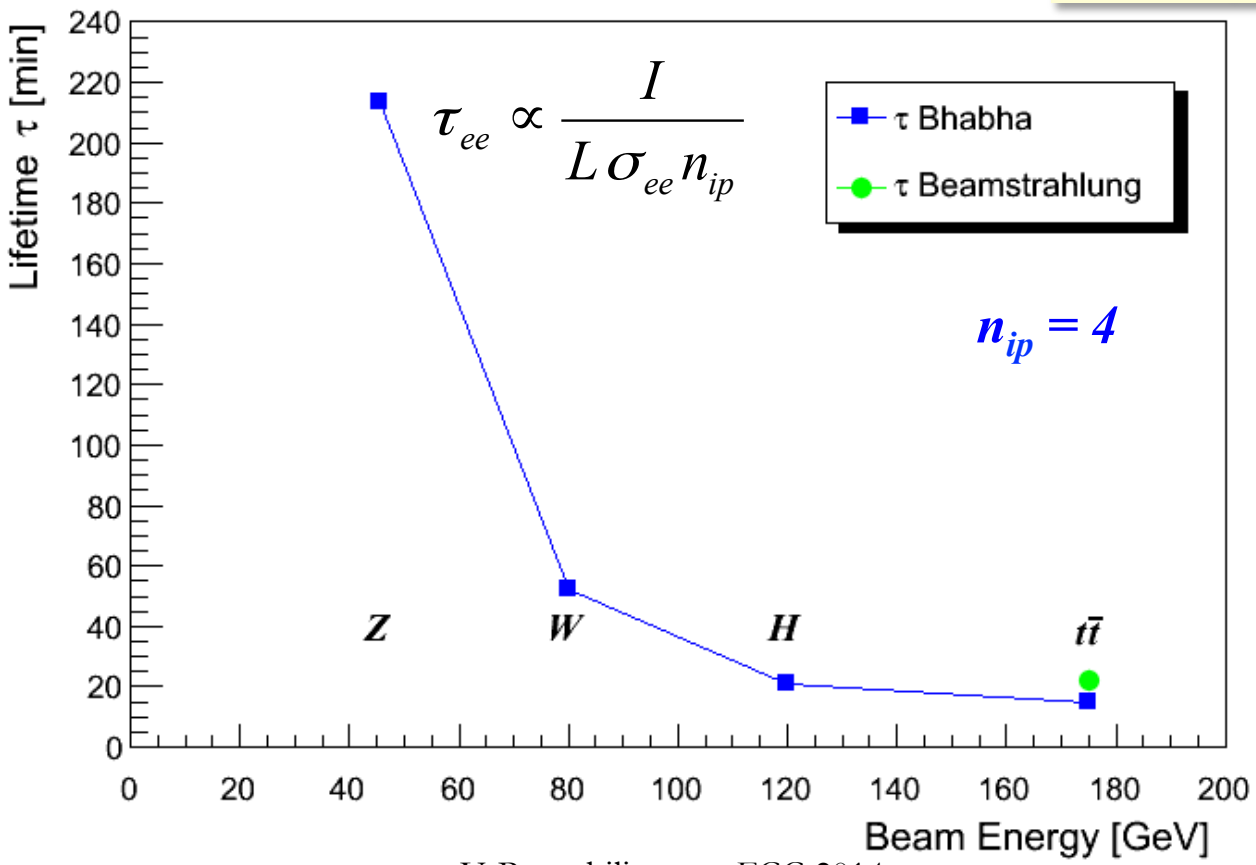
- Target parameters for injector
  - Repetition rate, particle flux
- LEP injector parameters
  - LIL and EPA, PS and SPS
- SUPERKEKB injector
- CLIC injector
  - CTF3 use and SPS as damping ring
- Top-up issues
  - PEPII, KEKB, X-ray storage rings
- Injection schemes
- Outlook and future work (injector work units)

TLEP Luminosity lifetime

- Lifetime from luminosity depends on radiative Bhabha scattering total cross-section $\sigma_{ee} \approx 0.21$ (b) $\approx$ constant with energy (LEP).

  $\Rightarrow$ Lifetimes down to ~15 minutes.

Continuous injection (top-up)

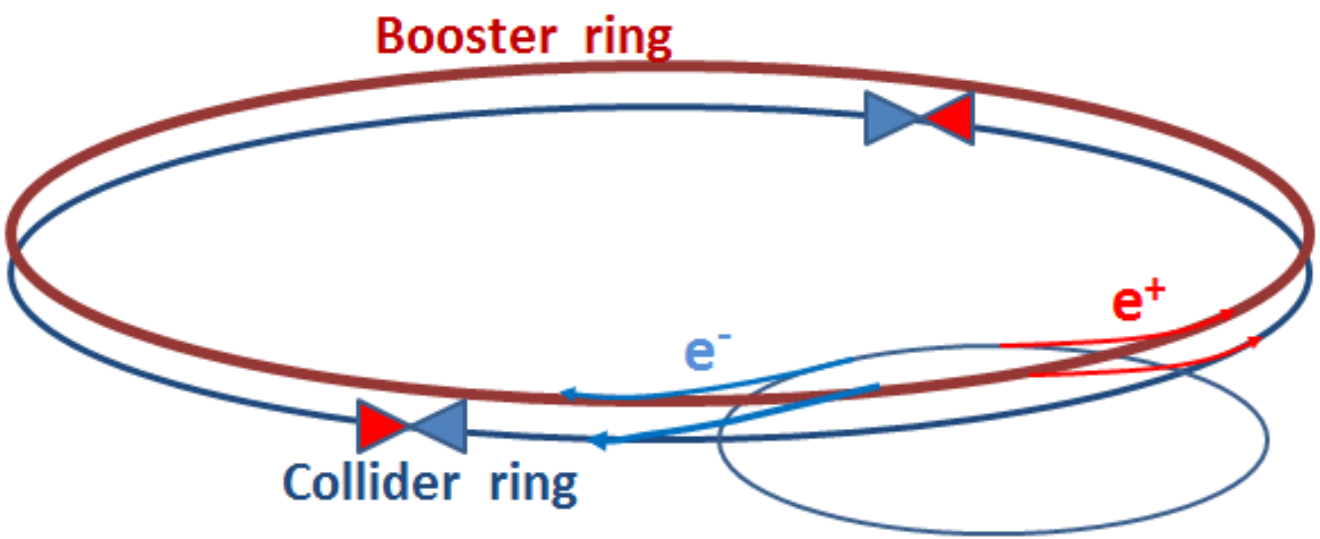


J. Wenninger – FCC kick-off 2014

Booster ring considerations

- Besides the collider ring(s), a booster of the same size (same tunnel) must provide beams for **top-up injection**.
  - Same size of RF system, but low power (~ MW).
  - Top up frequency ~0.1 Hz.
  - Booster injection energy ~20 GeV
  - Injector field at 20 GeV only ~ 60 G
  - Long chicanes for by-passing experiments
- **Injector complex for e+ and e- beams of ~20 GeV**

J. Wenninger, FCC kick-off 2014



Target injector parameters

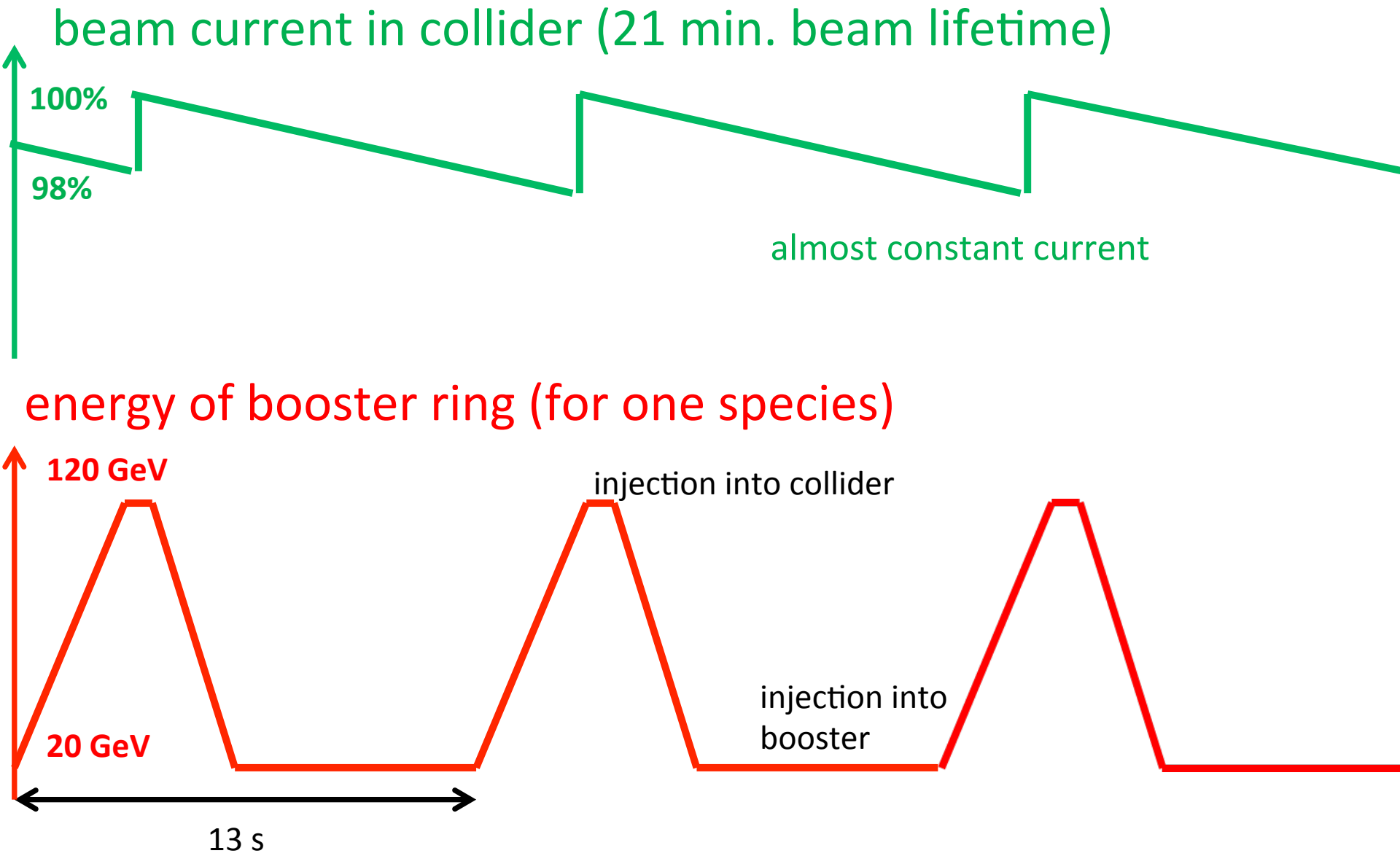
J. Wenninger – FCC kick-off 2014

Parameter	Z	W	H	tt	LEP2
E [GeV]	45.5	80	120	175	104
I [mA]	1400	152	30	7	4
No. bunches	16700	4490	1330	98	4
Bunch population [10^{11}]	1.8	0.7	0.46	1.4	4.2
Lifetime [min]	213	52	21	15	310
Time between injections [sec]	**129**	**32**	**13**	**9**	**188**
Injected total bunch population [10^{11}]	601.2	62.9	12.5	2.7	0.336
Injected particle flux for top-up [10^{11} p/sec]	**4.7**	**2.0**	**1.0**	**0.3**	**0.002**
Injected particle flux for full filling [10^{11}p/sec]	**225.5**	**23.6**	**4.6**	**1.0**	**0.13**
Booster injector ramp rate [GeV/sec]	**0.39**	**3.77**	**15.6**	**35.2**	**0.89**

- For defining injector cycle and flux assumed **2%** of current decay between top-ups and interleaved e^+/e^- injection
- Assumed **20min** for full collider filling (0.25mA/min for LEP) and the fastest possible cycle (~**9sec**)
- Need margin for transfer efficiency along the injector chain (**20%** of overhead)
- Ramp rate considering linear ramp and short flat bottom and flat top (~100ms)
- Note that LEP2 injector parameters are obtained with the same assumptions

Schematic top-up cycle

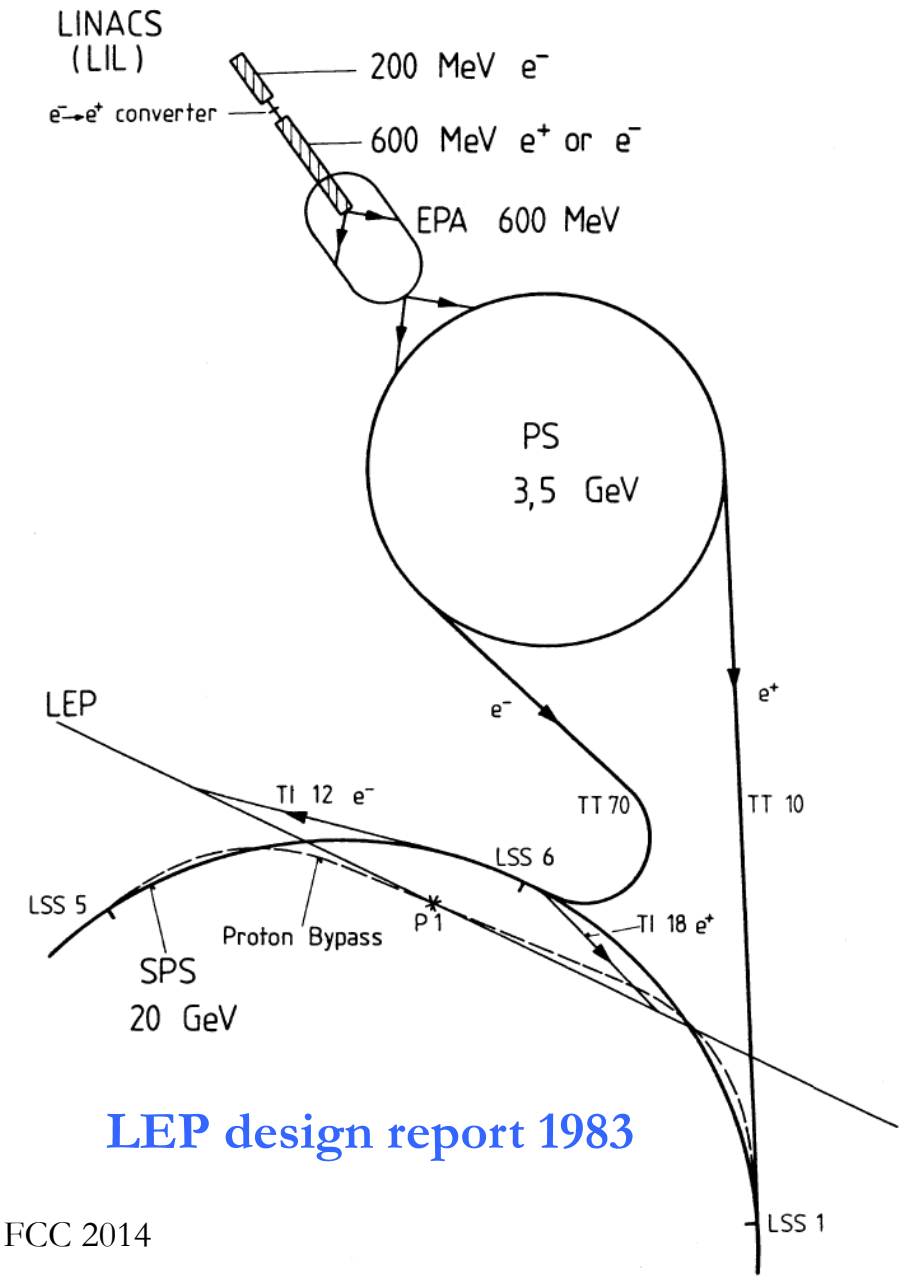
F. Zimmermann, 2013



A bit of history…
The LEP injector complex

LEP injector layout

- Pre-injector included and e^+/ e^- linac at 500 MeV (LIL), and accumulator (EPA)
  - Dismantled and many equipment re-used in CTF3
- Transferred through PS (@3.5GeV) to SPS
- Transfer line for positrons as for protons (TT2-TT10) and anti-proton line used for electrons (TT70-TT60, completely dismantled, as well as BT elements)



LEP design report 1983

LEP pre-injector parameters

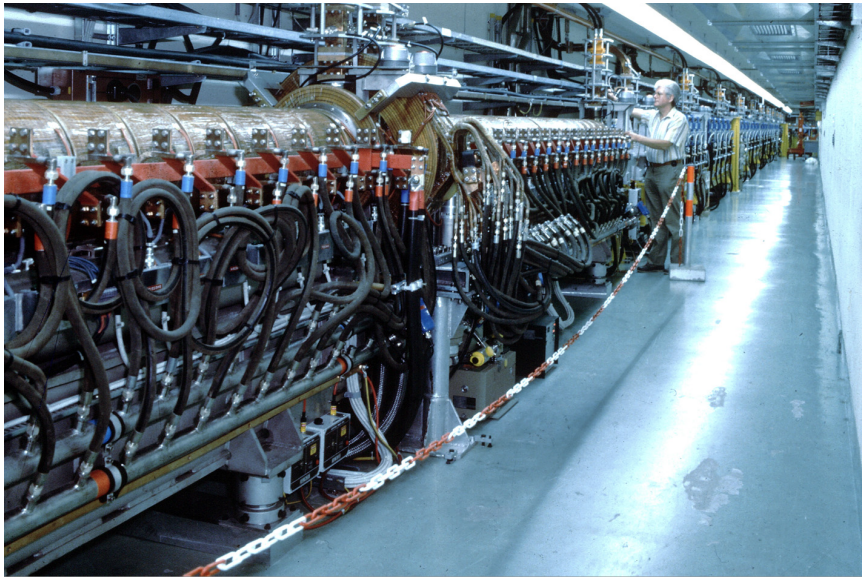
L. Rinolfi

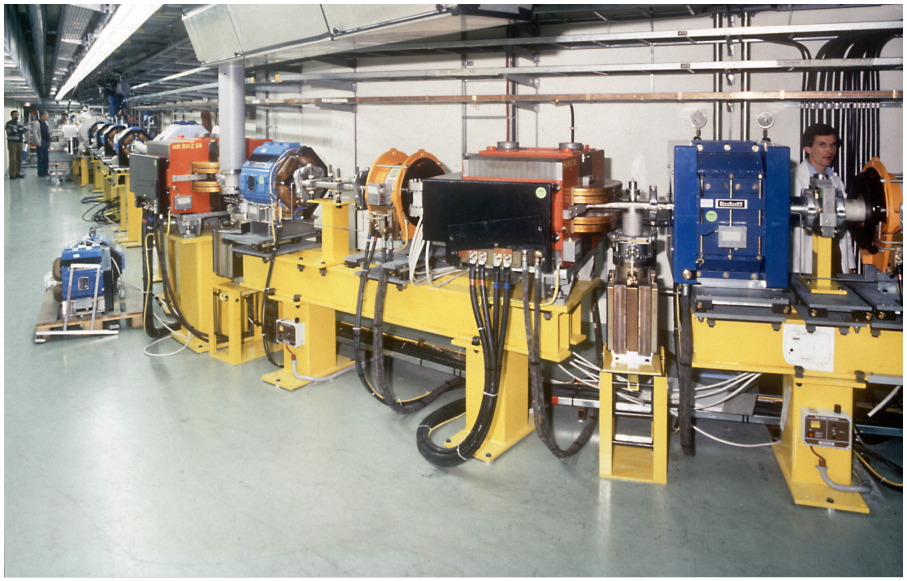
Parameters	LIL e-	EPA e-	LIL e- for e+	EPA e+
energy [GeV]	0.2 to 0.7	0.500	0.200	0.500
bunch population [10^{10}]	2		0.5 to 20	
bunch length [ps]	15		15	
bunch interval [ns]	0.333		0.333	
beam pulse length [ns]	10		10 to 50	
Beam sizes [mm] (rms)	3		1	
Flux [10^{11} p/s]	20			0.7
repetition rate [Hz]	100	0.83	100	0.09
Number of bunches		1 to 8		1 to 8
Max. bunch population [10^{11}]		4.5		3

- Flux for electrons quite high, much lower for positrons
  - Injection efficiency through the injectors almost 100%
  - **Betatron** Injection efficiency to LEP was **~50%** (filled machine)
  - **Alternative** injection scheme was necessary for pushing injection efficiency to **~85%** (see below)
- Positron accumulation time quite long

LPI – LEP Pre-Injector

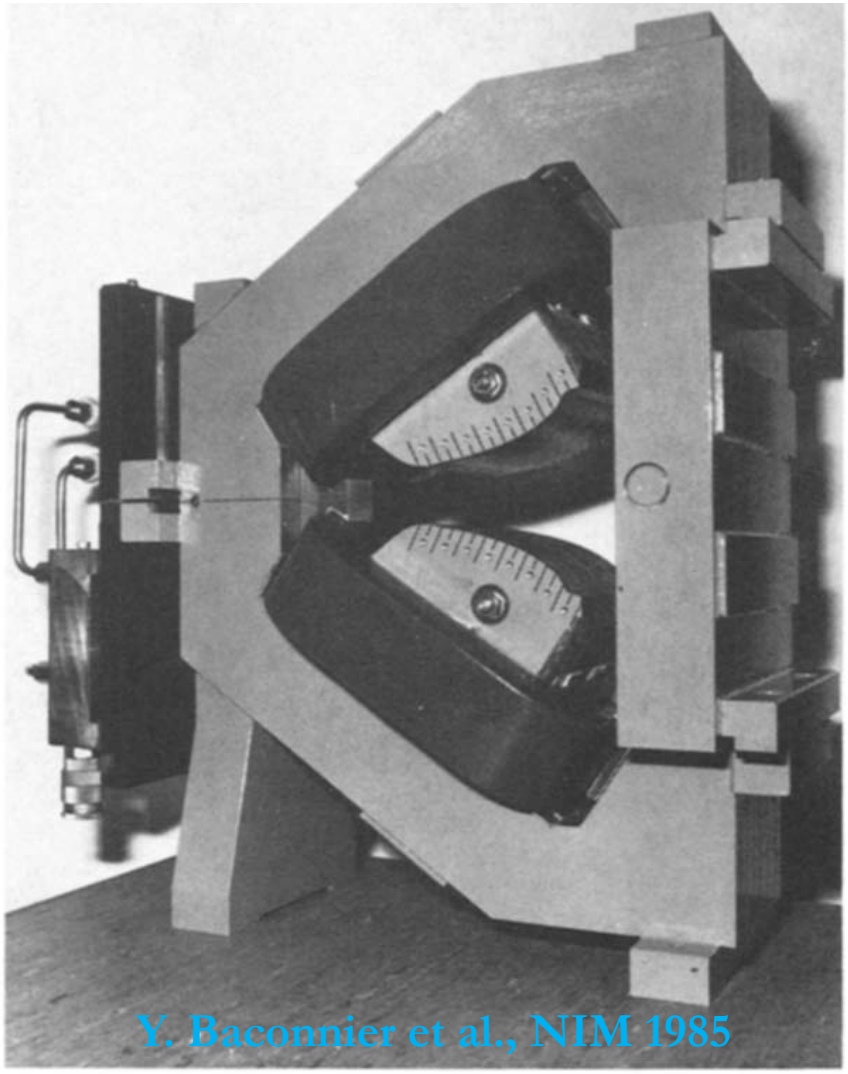
- 500 MeV e-/e+ into the PS
- EPA storage ring had 1/5 of PS circumference (40 π m=125.66m) => multi-bunch transfer to PS
- 19.1 MHz RF system, 50 kW, h=8
- e+ production by 200 MeV linac + W-target





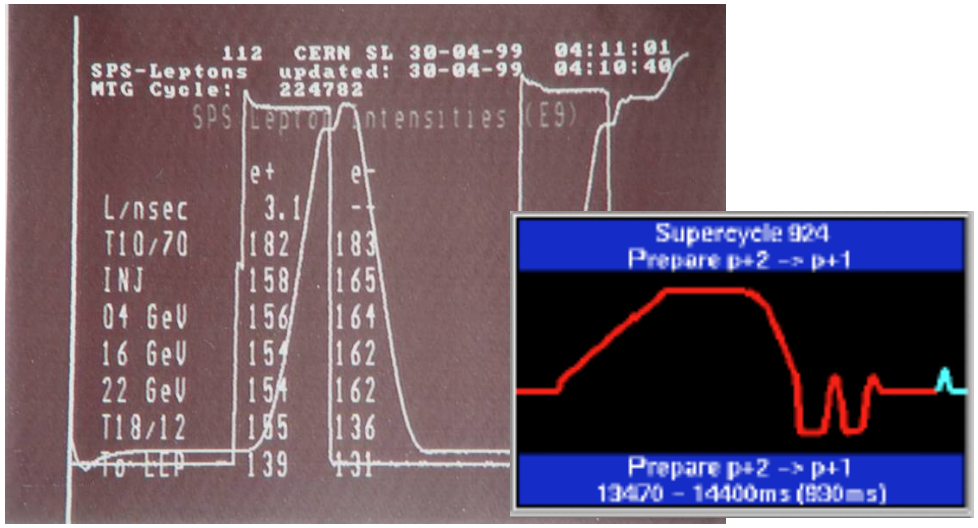
Leptons through PS to SPS

- Injecting at 500 MeV and extracting at 3.5 GeV
- 114 MHz RF system (2x500kV, 2x50kW), taken out in 2001
  - Robinson wigglers controlling damping partition (beam stability and reduced energy spread)
- RF had special 'expansion' of the longitudinal emittance



SPS as LEP Injector

P. Collier – Academic Training 2005



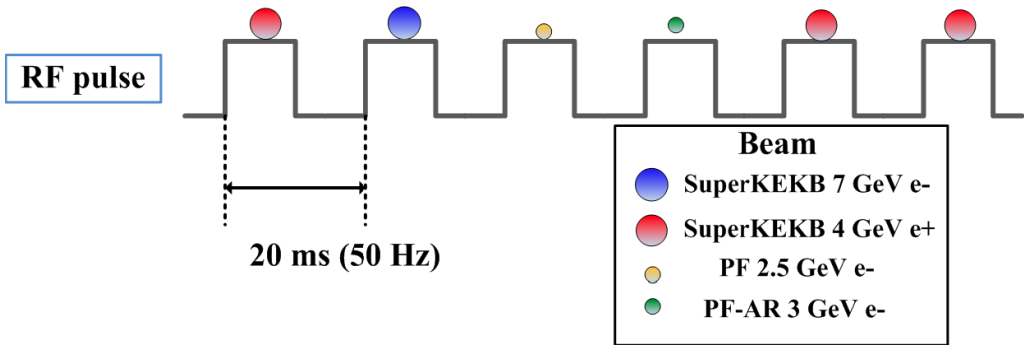
- LEP filling interleaved with FT proton operation
  - Initially supercycle of **14.4s** and later **12s**
- 4 cycles with 4 bunches ($2e^+$, $2e^-$) evolved to 2 cycles with 8 bunches (~**2.5×10^{10}** p/b)
- Energy to LEP: 18 → 20 → 22 GeV
- Lots of RF for leptons (200MHz SWC, 100MHz SWC, 352MHz SC),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

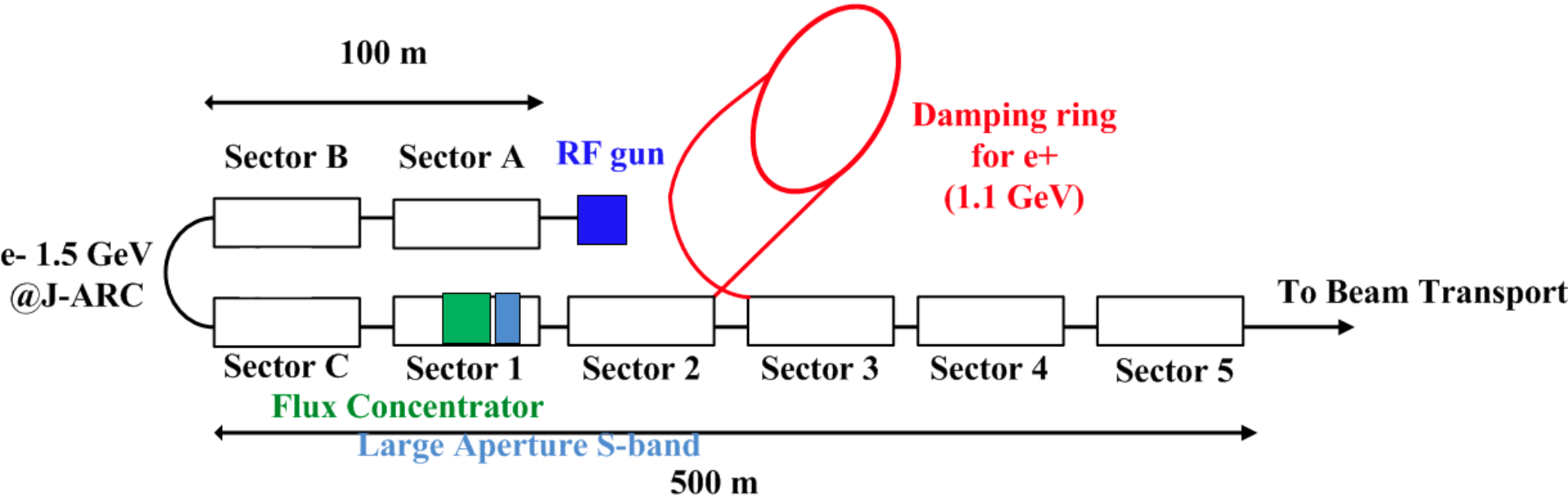
- Flux of **1.7×10^{11}** p/s for each cycle
  - Divided by 2 for interleaved injection and by 10 for complete supercycle
- **Incompatible** with lepton flux requirements for Z and W production (full machine filling)
- Need to be stretched for H and tt
- Lepton acceleration to **20GeV not possible** (~**30MV RF** needed and **not compatible** with present proton program)
- Ramp rate of **62.3GeV/s** provides factor of 2 margin, i.e. even **5sec cycle** possible
  - Ramp rate can be even faster due to low field requirements (maybe ~1Hz possible)

SuperKEKB injector

- Lifetime of 6min necessitates top-up
- Injector should serve 4 rings
  - Repetition rate 50Hz
- Positron flux rate at **2.5×10^{12}** p/sec is **compatible** with TLEP needs (apart for Z production parameters)
- Commissioning of the injector has already started
  - **Collaboration** with KEK colleagues essential for gaining experience

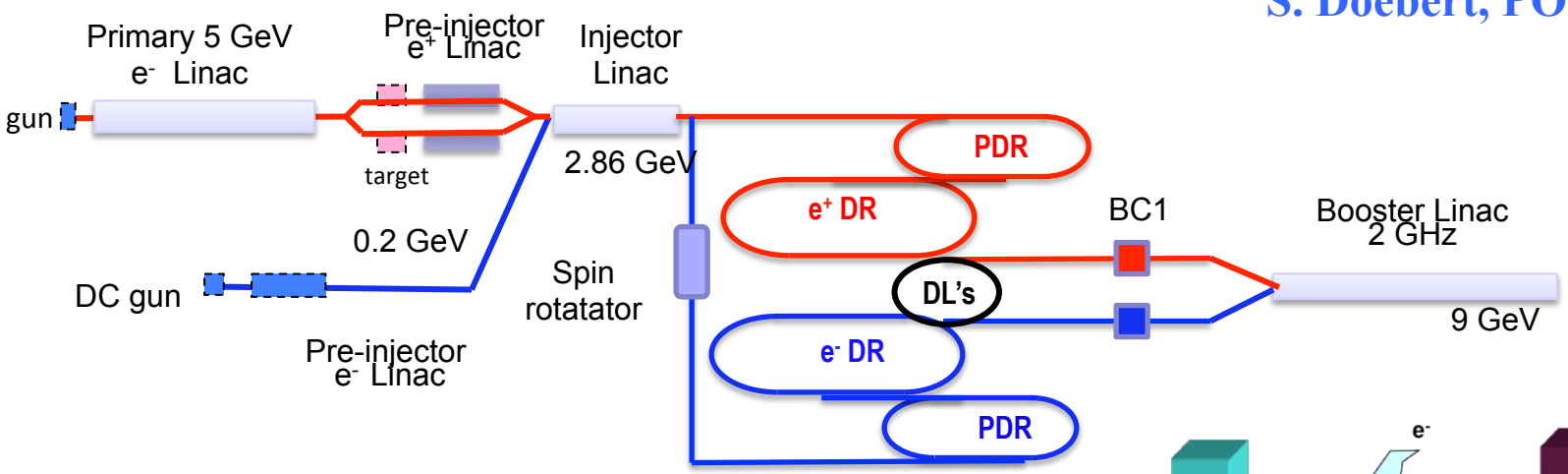
See talk by K. Oide



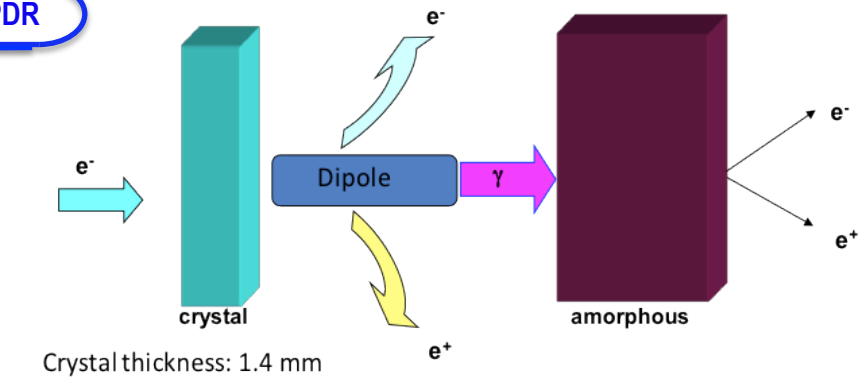


CLIC Main Beam Injector Complex

S. Doebert, POSIPOL 2013



- Two hybrid positron sources (only one needed for 3 TeV collider)
- Common injector linac
- All linac's at 2 GHz, bunch spacing 1 or 2 GHz before the damping rings



Crystal thickness: 1.4 mm
Oriented along the <111> axis

Distance (crystal-amorphous) d = 2 m

Amorphous thickness e =10 mm

Target Parameters Crystal		
Material	Tungsten	W
Thickness (radiation length)	0.4	χ_0
Thickness (length)	1.40	mm
Energy deposited	~1	kW

Target Parameters Amorphous		
Material	Tungsten	W
Thickness (Radiation length)	3	χ_0
Thickness (length)	10	mm
PEDD	30	J/g
Distance to the crystal	2	m

Positron flux for future colliders

L. Rinolfi

	SLC	CLIC (3 TeV)	CLIC (0.5 TeV)	ILC (RDR)	LHeC (pulsed)	LHeC ERL
Energy [GeV]	1.19	2.86	2.86	5	140	60
e^+/ bunch (at IP)	40×10^9	3.7×10^9	7.4×10^9	20×10^9	1.6×10^9	2×10^9
e^+/ bunch (aft. capture)	50×10^9	7×10^9	14×10^9	30×10^9	1.8×10^9	2.2×10^9
Bunches / macropulse	1	312	354	2625	100 000	NA
Rep. Rate (Hz)	120	50	50	5	10	CW
Bunches / s	120	15600	17700	13125	10^6	20×10^6
e^+ flux [10^{14}p/s]	0.06	1.1	2.5	3.9	18	440

- CLIC injector positron flux **satisfies TLEP requirements** for all energies
  - Leaves 50% margin for capture and transfer losses
  - Design quite mature (un-polarized positron)
  - Need **damping ring** (for positrons)
  - Different bunch structure and **20GeV linac** for injecting into booster ring
- ILC injector also satisfies flux requirements, but polarised positron production necessitates 250GeV drive beam through helical undulator (**not compatible with TLEP**)
- **LHeC** is orders of magnitude above requirements (challenging design)

SPS as damping ring

- Reviving old ideas, when SPS was running also as a LEP injector
- More recent ones, serving as e+ DR for LHeC
- Can be used for for testing components and interdependencies in similar beam conditions in the presence of synchrotron radiation (scrubbing with leptons?)

Evans and Schmidt, 1988

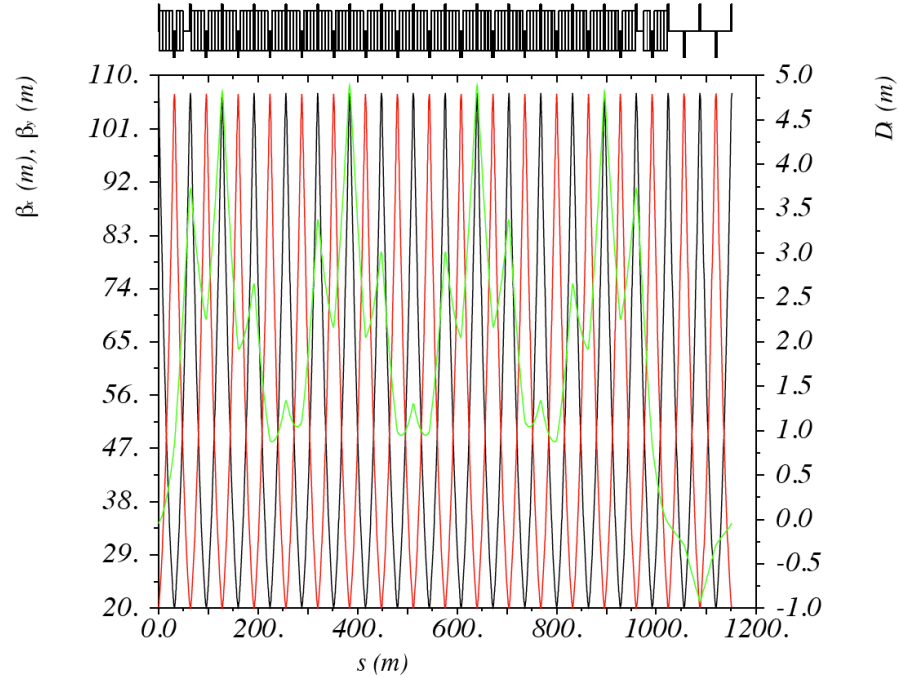
A	B	F	G	H	I
VARIABLES		*WITH WIGGLER*		Intrabeam scattering	
ETA	0.0018	brho	13.3424	ep	0.001637
VOLTS(V)	4.00E+07	wiggler deflection	0.00356	A	3.9E-06
Q VALUE	27	Bending radius	14.04463	k	0.005958
MOMENTUM COMPAC	0.0018	2*pi*rho^2	1239.369	a	0.003439
BETA (V/C)	1	F	0.005544	d	0.997034
ENERGY DPN JE	2	***Parameters With wiggler on***		Inc2a	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		

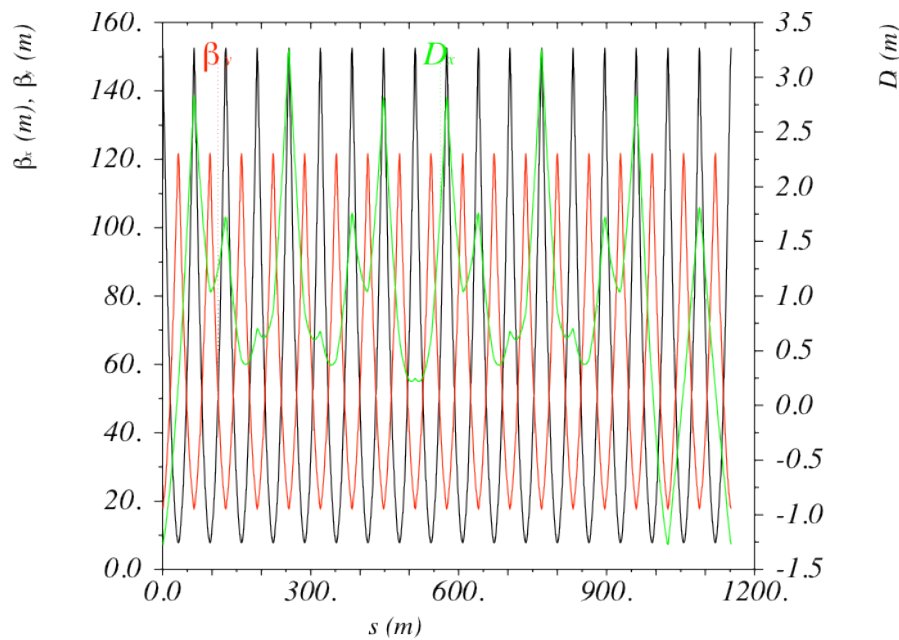
Parameter [unit]	High Rep-rate	Low Rep-rate
Energy [GeV]	10	7
Bunch population [10^9]	1.6	1.6
Bunch spacing [ns]	2.5	2.5
Number of bunches/train	9221	9221
Repetition rate [Hz]	100	10
Damping times trans./long. [ms]	2/1	20/10
Energy loss/turn [MeV]	230	16
Horizontal norm. emittance [μm]	20	100
Optics 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

LHeC design report 2011

SPS low emittance optics

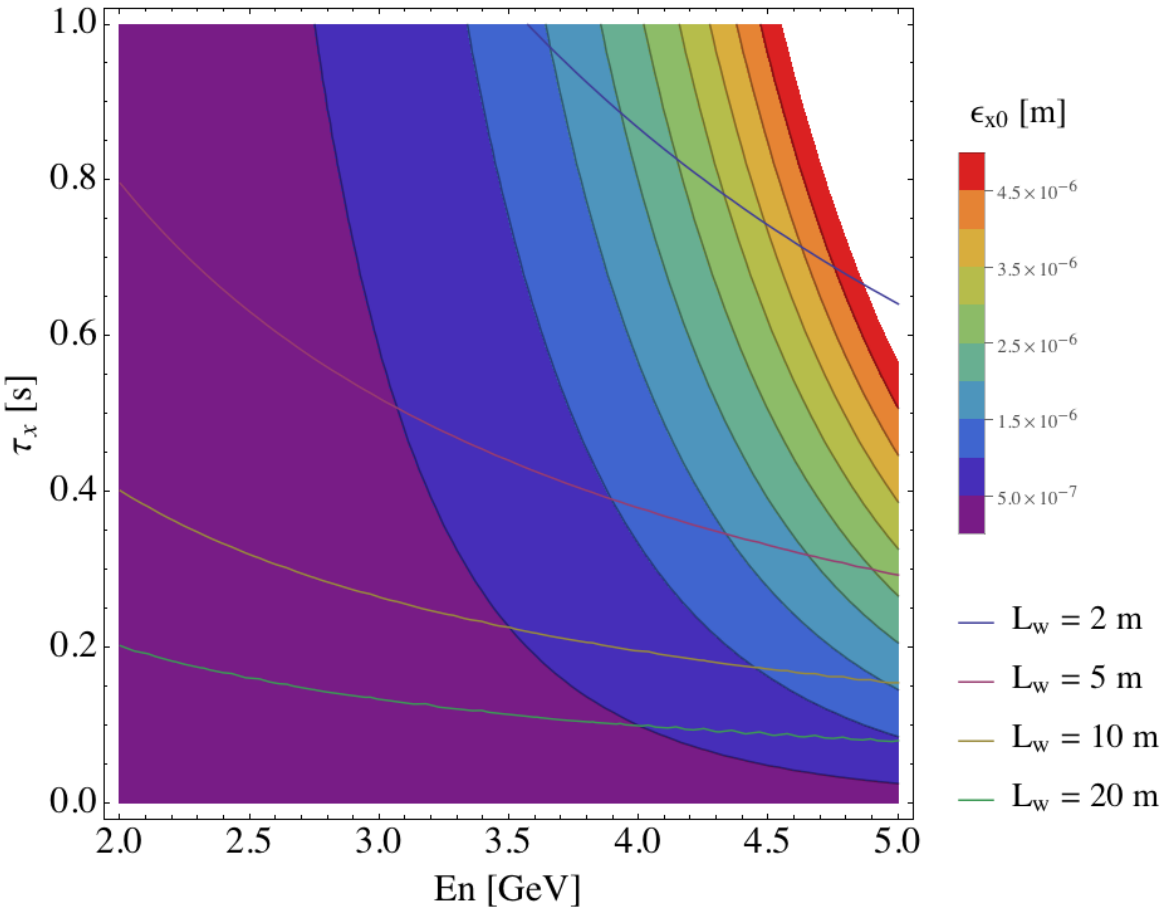
- SPS is an all FODO cell lattice (6 sextants), with missing dipole
- Usually tuned to 90 deg. phase advance for fixed target beams (**Q26**) and since 2012 to 67.5 deg (**Q20**) for LHC beams
- Move horizontal phase advance to 135(3π/4) deg. (**Q40**)
- Normalized emittance with nominal optics @ 3.5GeV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





Emittance scaling

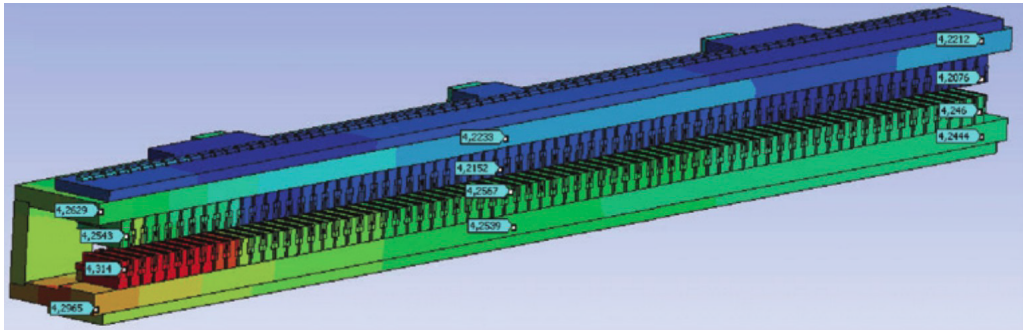
- Energy and damping time can be parameterised with equilibrium emittance, for different wiggler lengths
- Ultra-low emittance achieved in energy range between 2 to 5GeV

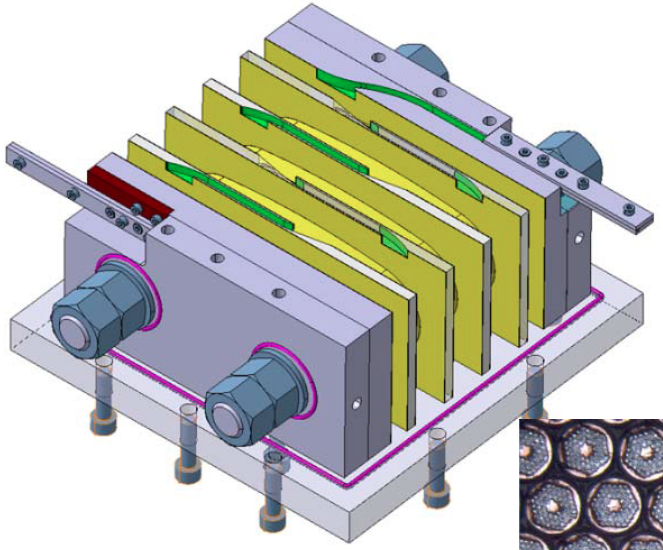


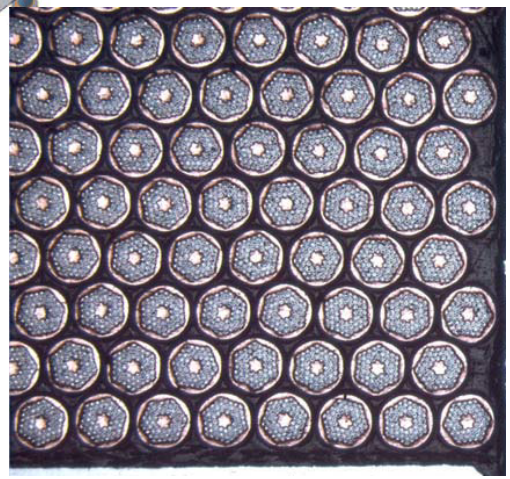
- A few meters of damping wigglers can be used (and higher energy) for short damping times
- Available RF voltage sufficient up to ~10GeV (without wigglers)

SC wiggler development

A. Bernard, P. Ferracin, N. Mesentsev, S. Hillenbrad, L. Garcia-Fajardo, et al. CLIC workshop 2014







- Two paths of R&D
  - NbTi wire, horizontal racetrack, conduction cooled (BINP/KIT collaboration)
  - Nb_3Sn wire, vertical racetrack, conduction cooled (CERN)
- Full NbTi length prototype
  - Higher than 3T, 5.1cm period, magnetic gap of 18mm
  - Under production by BINP to be installed in (summer 2014) in ANKA for beam tests
  - Operational performance, field quality, cooling concept
- First Nb_3Sn vertical racetrack magnet (3-period) tested in 2011
  - Reached 75% of max. current
  - Limited by short coil-to-structure (insulation)
  - New short model under development (optimised impregnation,

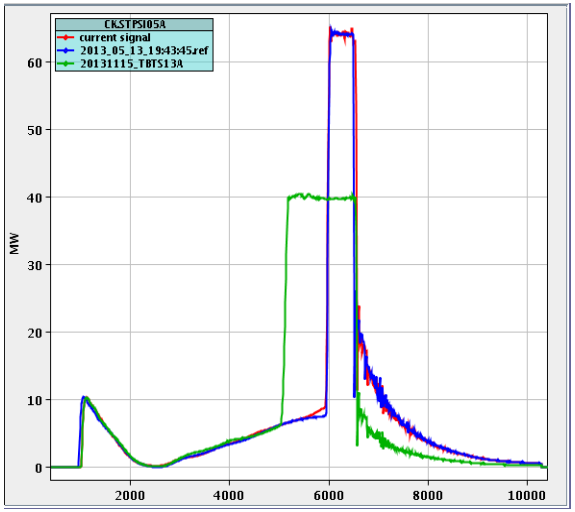
SPS DR parameters

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	3.7	20.5	32.5
Energy spread [%]	0.011	0.13	0.11	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				

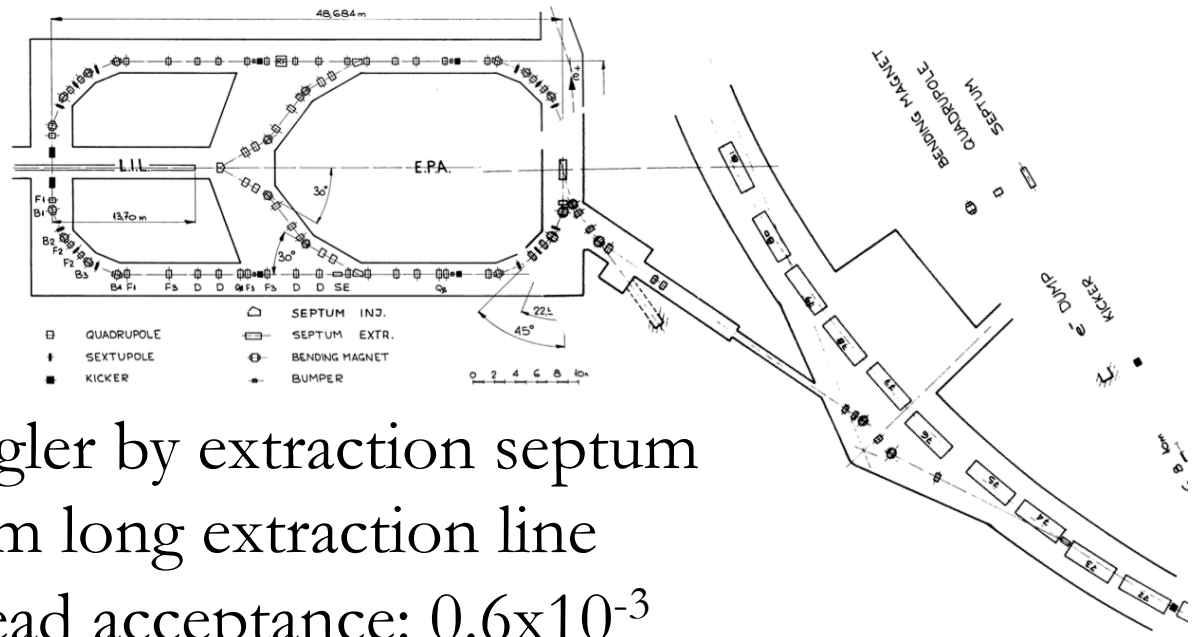
- Need to revive lepton injector complex…

CTF3 injection into PS

R. Corsini, F. Tecker,
CLIC workshop 2014



- CTF3 has ~125 MeV (full beam-loading)
- Short pulse + low charge + 1 additional MKS > gain of ~ 3 in energy
- final energy: ≥ 380 MeV
- CR & TL1 bends good up to 450 MeV



- Replace CR wiggler by extraction septum
- Rebuild ~40-50m long extraction line
- Had energy spread acceptance: 0.6×10^{-3}

From the linac to SPS

Linac bunch structure

Single bunch (train) – need laser

≥ 5 ns spacing

≥ 25 ns spacing

3 GHz short bunch pulse (possibly repeated a few tin

R. Corsini, F. Tecker, CLIC workshop 2014

PS RF acceptance

$$\left(\frac{\Delta E}{E_s}\right)_{max} = \mp\beta\sqrt{-\frac{2e\hat{V}}{\pi h \eta E_s}}$$

- Maximum energy acceptance:
- E=400 MeV, η=-α=-0.027
- present 200 MHz system, h=420, 8*30kV
- => $\Delta E/E < 5.7\ 10^{-3}$

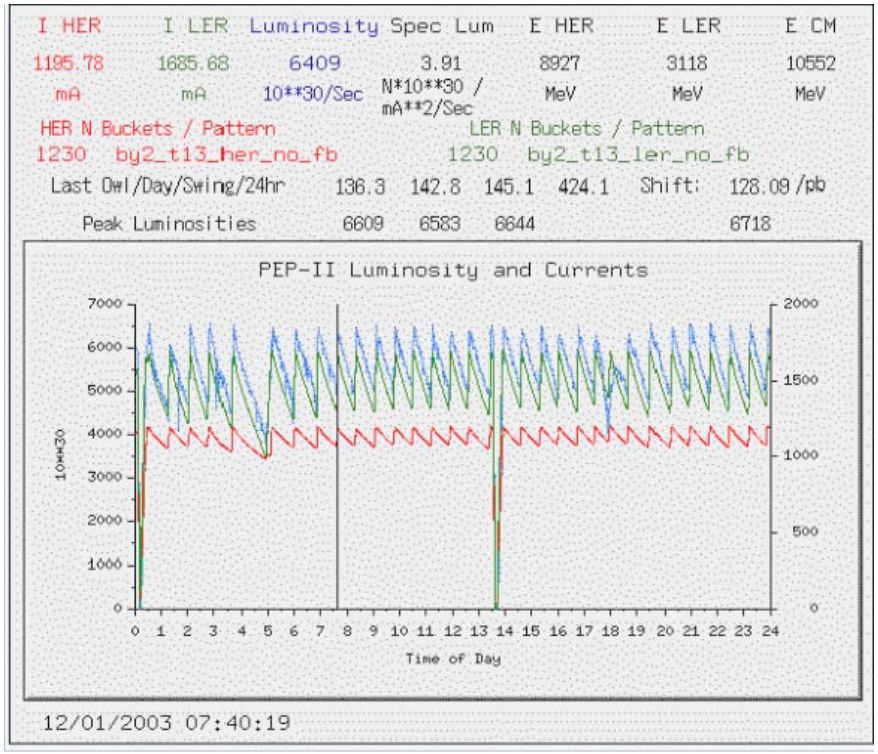
- 40/80 MHz systems have 2*/3*300kV, respectively
- => $\Delta E/E < 2\% / 1.75\%$

- 40/80 MHz do not match with the CR rev. frequency
- maybe direct injection into PS

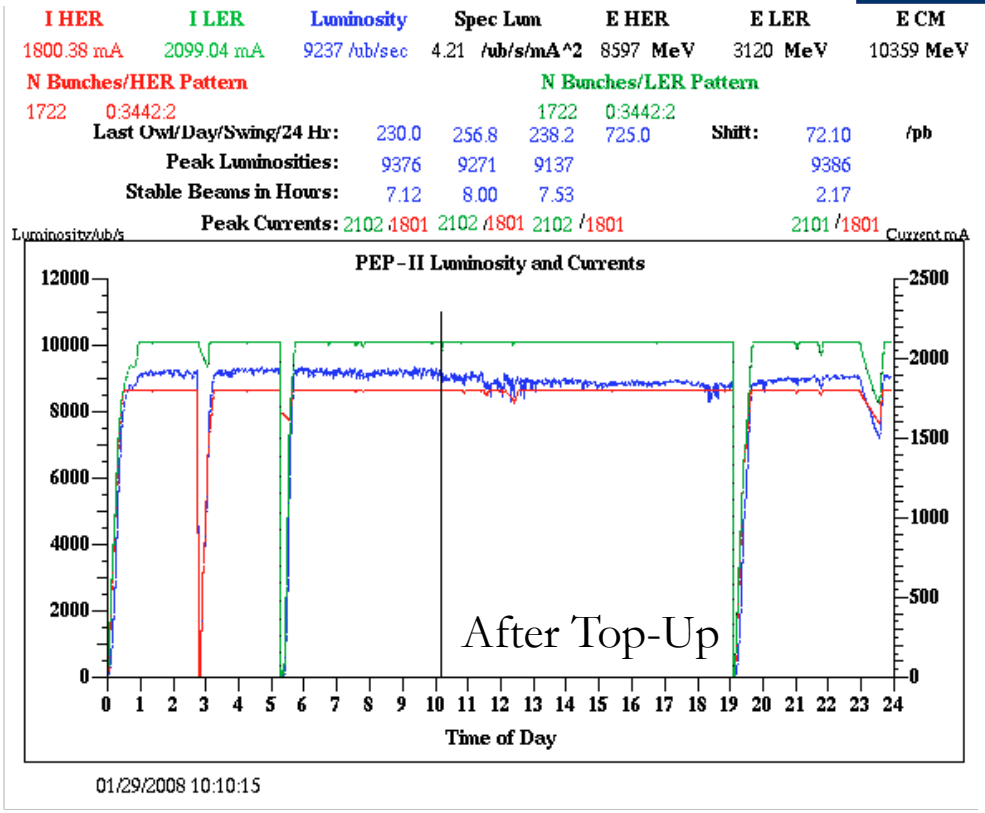
- Emittances looks OK even for direct transfer for e- (but not for e+)
- Bunch charge limitations to be checked without Robinson wigglers
- Transfer lines PS > SPS OK for e+, not for e- (transfer lines)
  - Generation of e+
- RF cavity, extraction septum in CR (case of accumulation) ?
- Injection/extraction elements in PS, SPS

Top-up considerations

Top-up at PEP-II/BaBar



Before Top-Up



J. Siemann, EPAC 2008

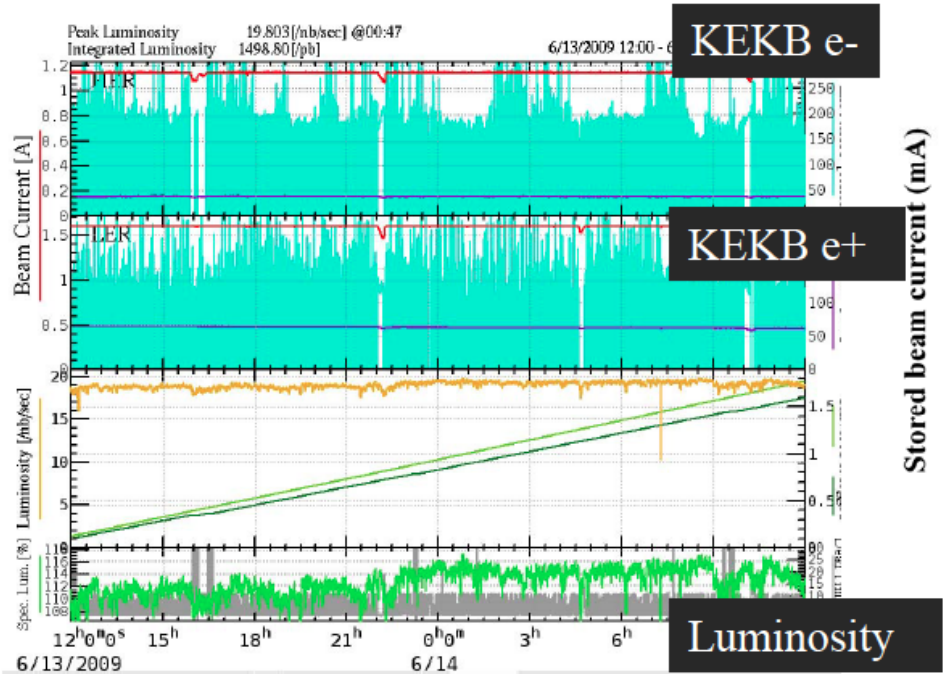
- Background signals provided by the BaBar detector gated on actual injection pulses
- Systematic improvements of the electron beam from the LINAC
- Reduction of the distance of the injected beam from the closed orbit
- Trajectory stabilization feedback
- Both ring kicker systems were upgraded

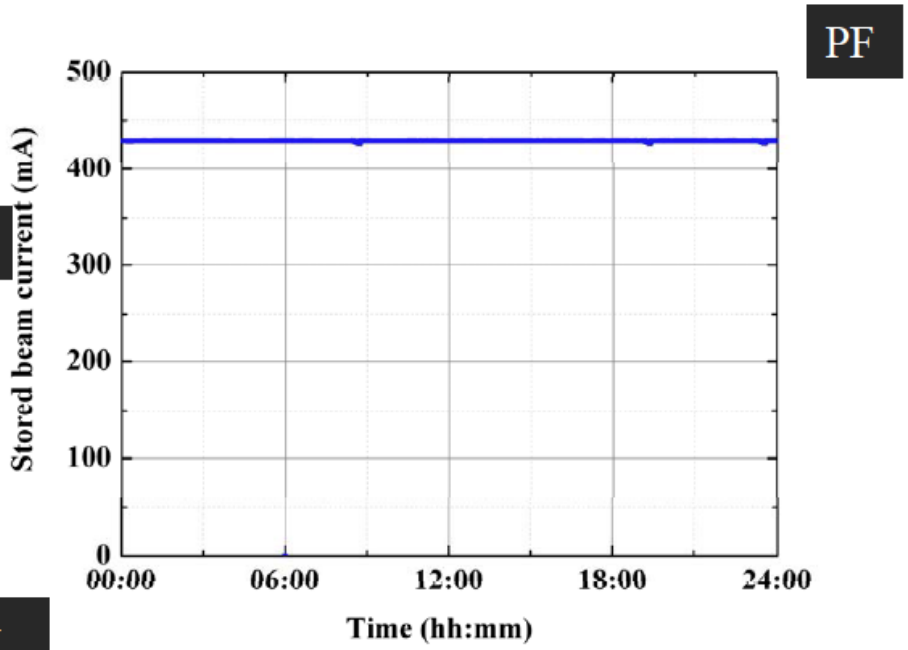
Top-up at KEKB

M. Satoh, SuperKEKB commissioning workshop 2013

Simultaneous Top-up Operation for three rings

- Stored beam current stability since Apr. 2009
  - KEKB: 1 mA (~ 0.05%) : e-: 12.5 Hz, e+: 25 Hz
  - PF: 0.05 mA (~ 0.01%) : 0.5 Hz





Top-up injection for light sources

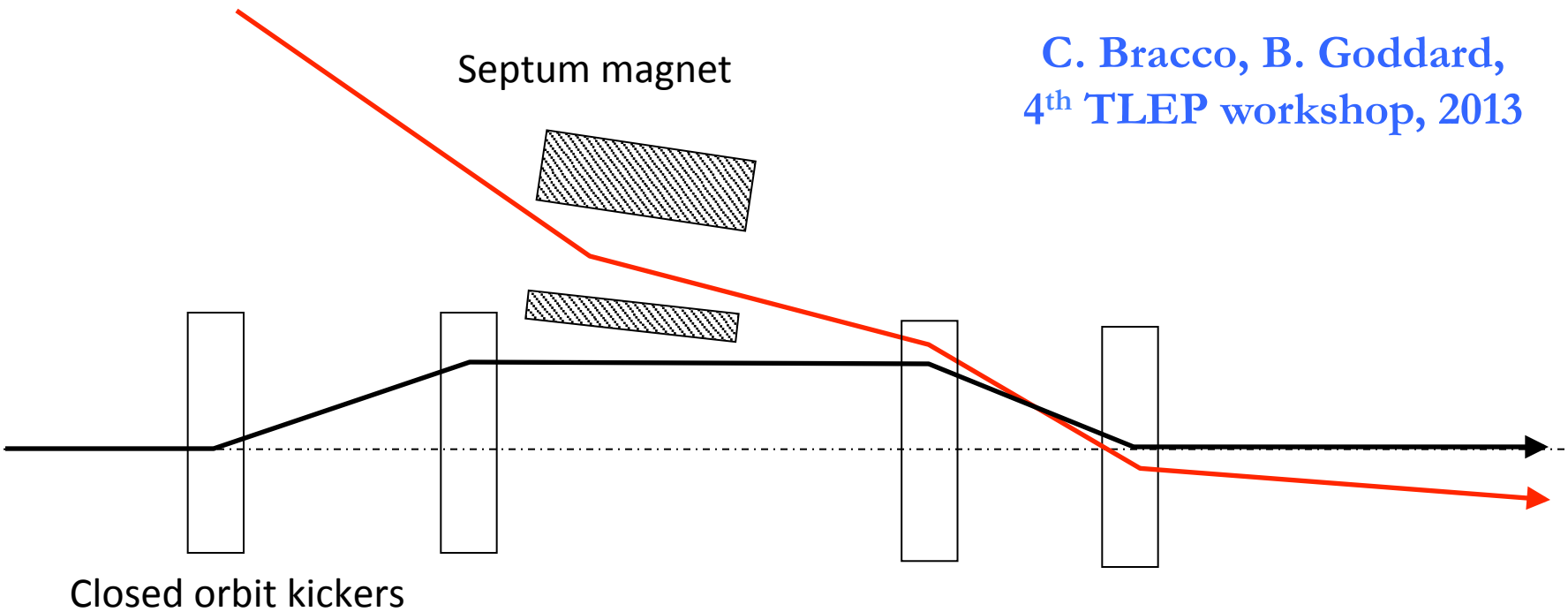
J.L. Revol, 2012

Two Operating Modes		Stability	Number of shots	Time between injection	
Injection at fixed Delta I	SPring 8	0.03 %	One	≈ 2 to 3 mn *Hybrid 10 to 30 sec*	One shot
	Bessy	0.13 %	One	≈ 20 to 30 sec	
	Soleil	0.5 %	One	≈ 2 to 5 mn	
	Elettra	0.3 %	20 shots	*≈ 6 mn at 2 GeV* *25 mn at 2.5 GeV*	Few shots
	SLS	0.5 %	10 shots	≈ 1 to 2 mn	
	Petra	1 %	40-50 low charge shots	≈ 8 mn *1 mn (timing mode)*	
Injection at fixed Delta Time	APS	≈ 0.5 %	One	1 and 2 mn	One shot
	Diamond	≈ 0.8 %	Few	10 mn	Few shots
	ESRF	≈ 20%	400	12 hours	

- Perturbations due to top-up
  - Bump closure, septum shielding, booster magnet field shielding, thermal drifts, blind-out of experiments during injection, reliability of booster ring, BT elements failures, orbit feed-back,…
- Study alternative injection schemes and innovative kicker technology

Betatron injection

- Beam is injected with a position/angle offset with respect to the closed orbit
- Injected beam performs damped betatron oscillations about the closed orbit
- Bump closure can be a major issue (stable and reproducible kickers)

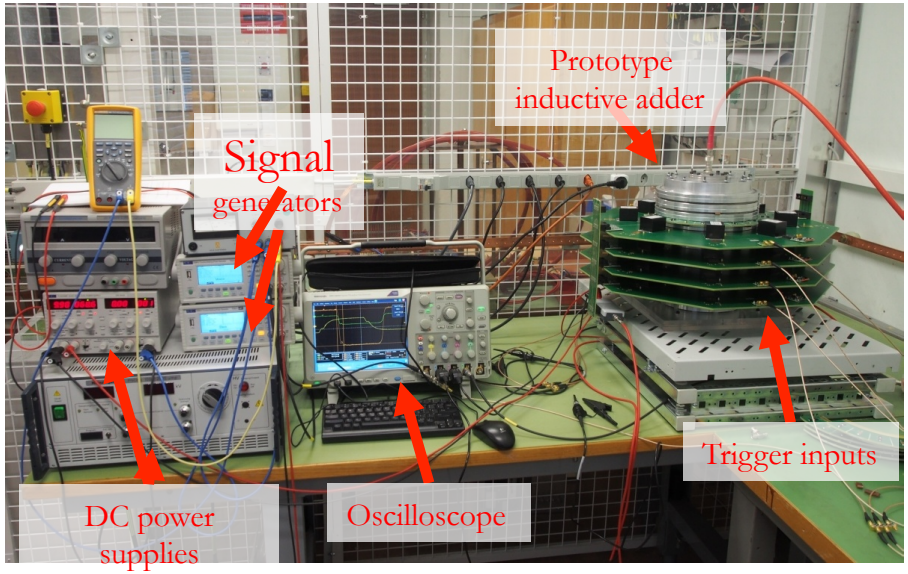


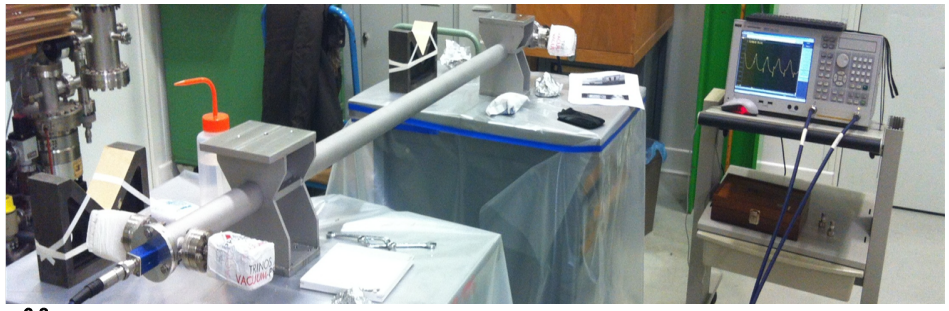
C. Bracco, B. Goddard,
4th TLEP workshop, 2013

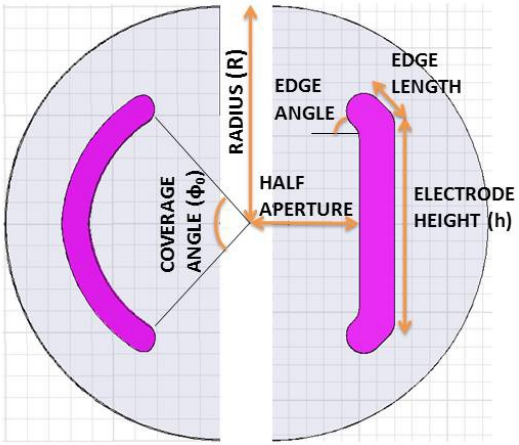
CLIC DR kicker

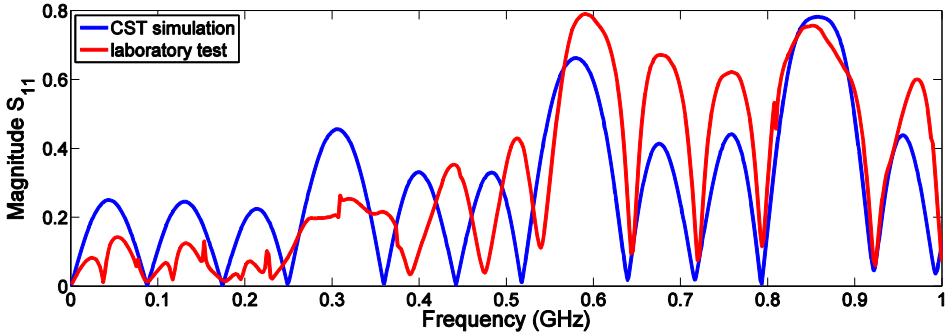
M. Barnes, J. Holma, C. Belver- Aguilar, A. Faus Golfe et al., CLIC workshop 2014

- Kicker jitter tolerance ~ few 10^{-4}
- Striplines required for achieving low longitudinal coupling impedance
  - Prototyped under the Spanish Program "Industry for Science"
  - Now, at CERN for laboratory tests
- Significant R&D done for pulser
  - First 5-layer inductive adder prototype under tests at CERN), second one to be assembled during this month
- Collaboration is set-up with ALBA synchrotron and ATF for beam tests



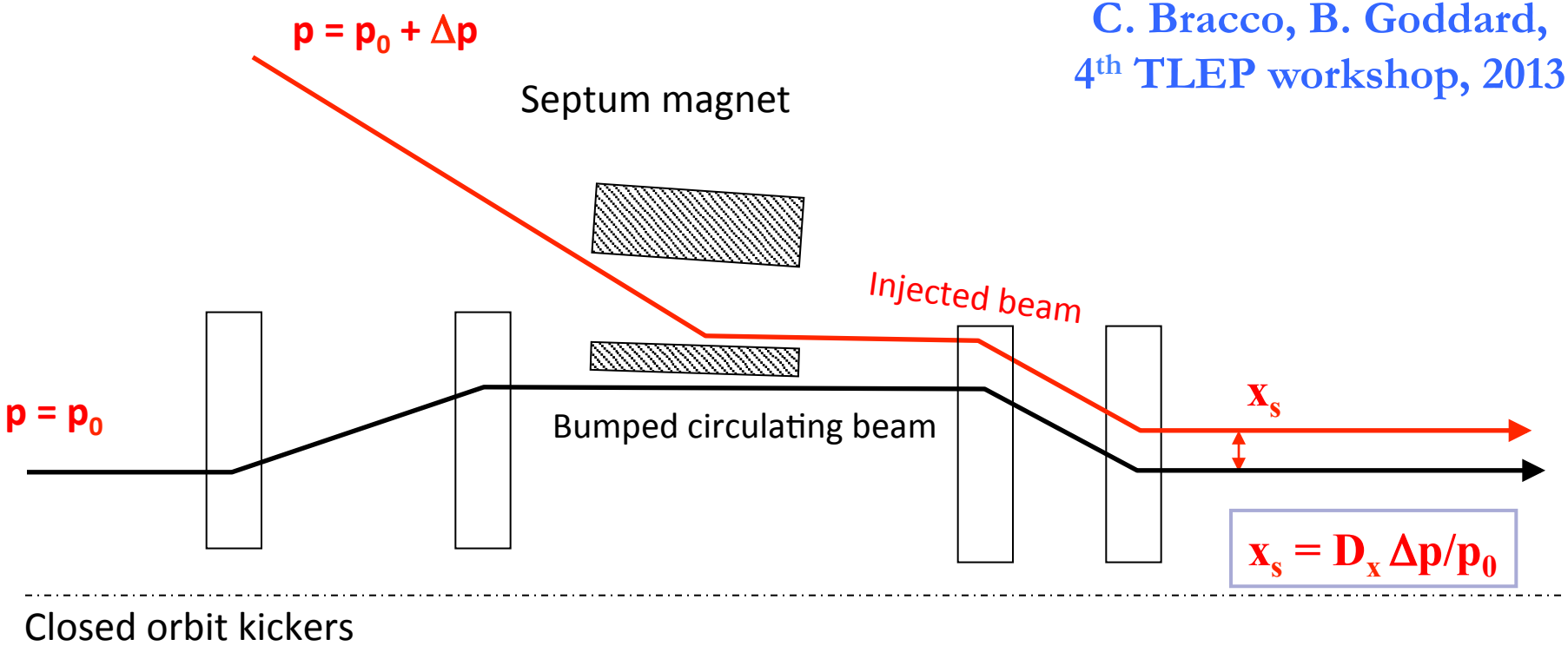






Synchrotron injection

C. Bracco, B. Goddard,
4th TLEP workshop, 2013

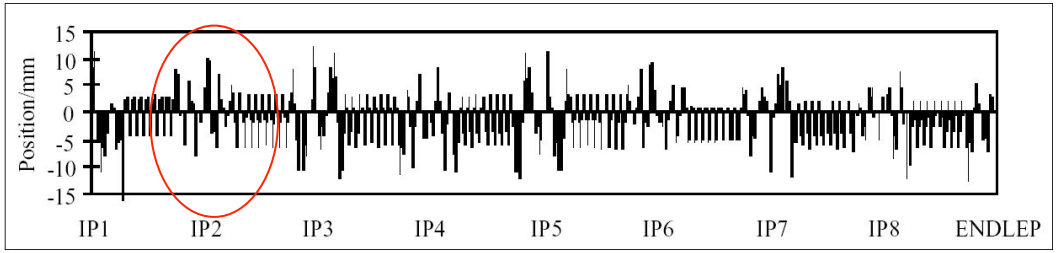


- Inject off-momentum
- Beam injected parallel to circulating beam, onto matched dispersion orbit of a particle having the same momentum offset $\Delta p/p_0$
- Injected beam makes damped synchrotron oscillations at synchrotron tune but does not perform betatron oscillations

Synchrotron injection at LEP

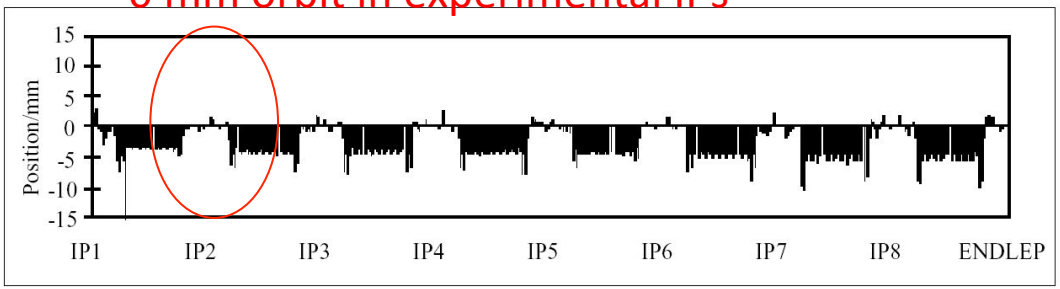
~10 mm orbit in experimental IPs

P. Collier, PAC 1995

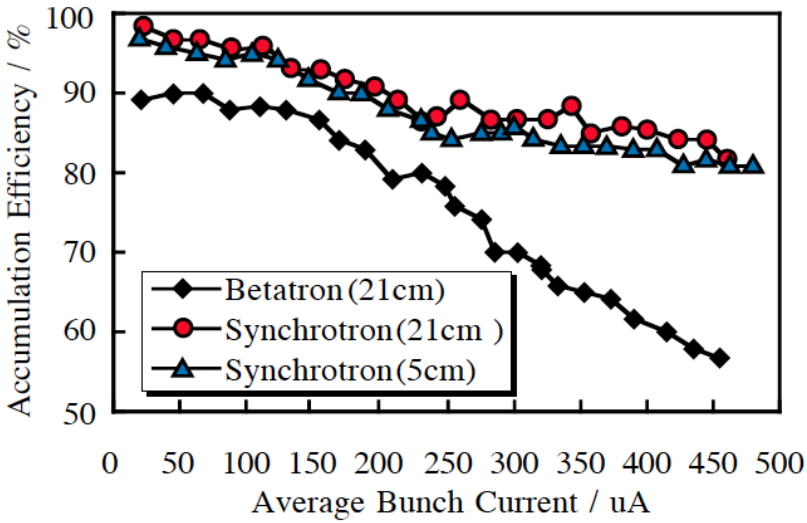


Optimized Horizontal First Turn Trajectory for Betatron Injection of Positrons into LEP.

~0 mm orbit in experimental IPs



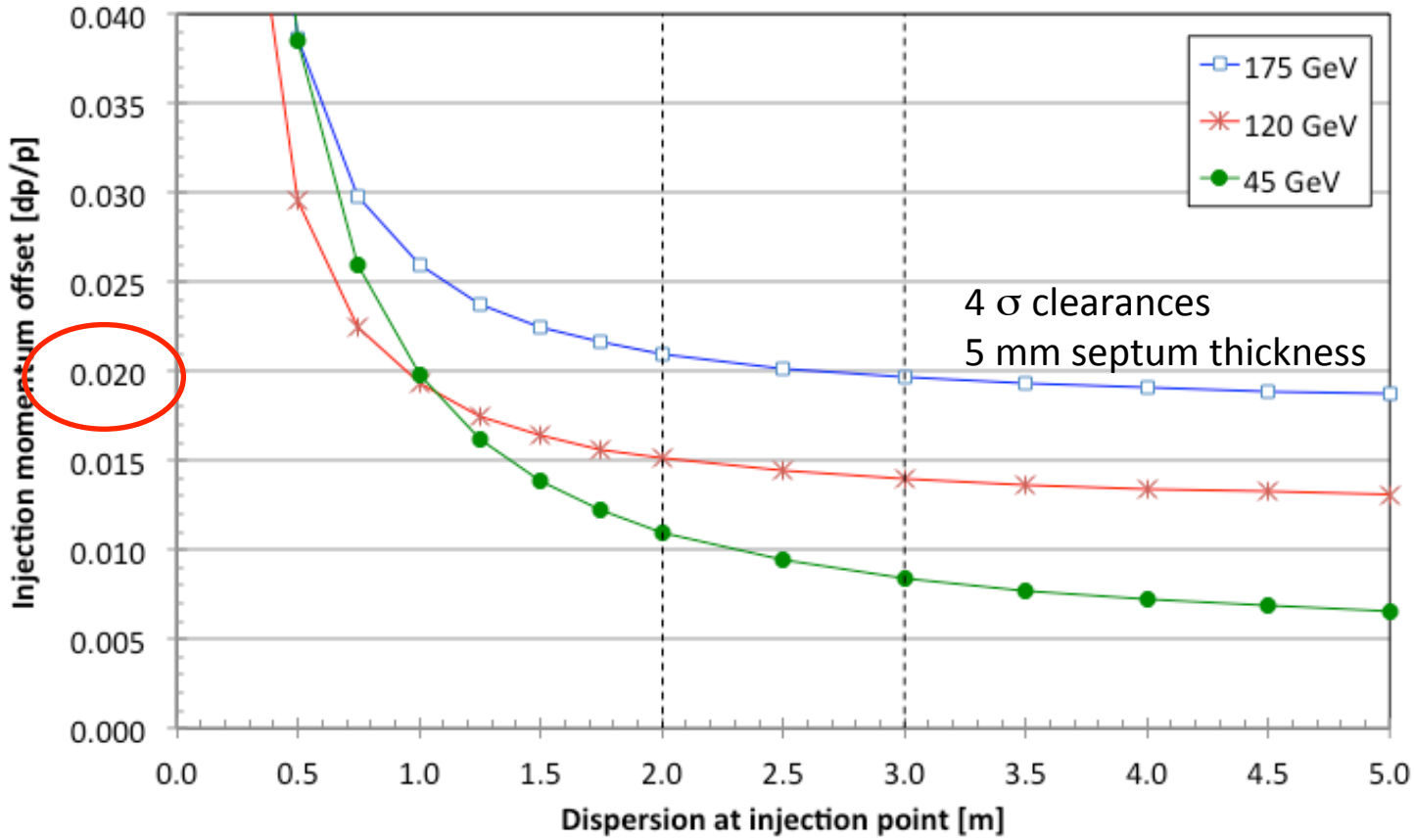
Optimized Horizontal First Turn Trajectory for Synchrotron Injection of Positrons with ΔP/P at -0.6%



- Synchrotron injection in LEP gave improved background for experiments due to small orbit offsets in zero dispersion straight sections
- It also improved greatly accumulation efficiency (85% for filled machine)

Dispersion vs momentum spread

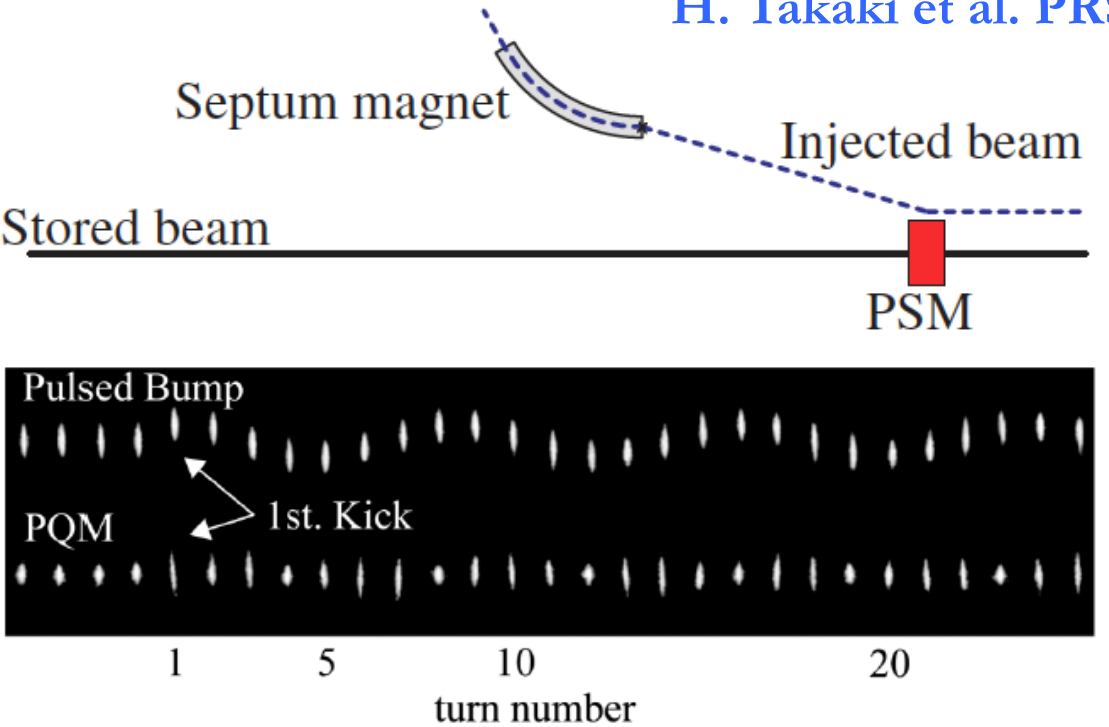
C. Bracco, B. Goddard, 4th TLEP workshop, 2013



- At 175 GeV would need to inject with 2% momentum offset
- Synchrotron injection gets difficult for higher energies due to momentum spread
- Marginal gain with larger dispersion

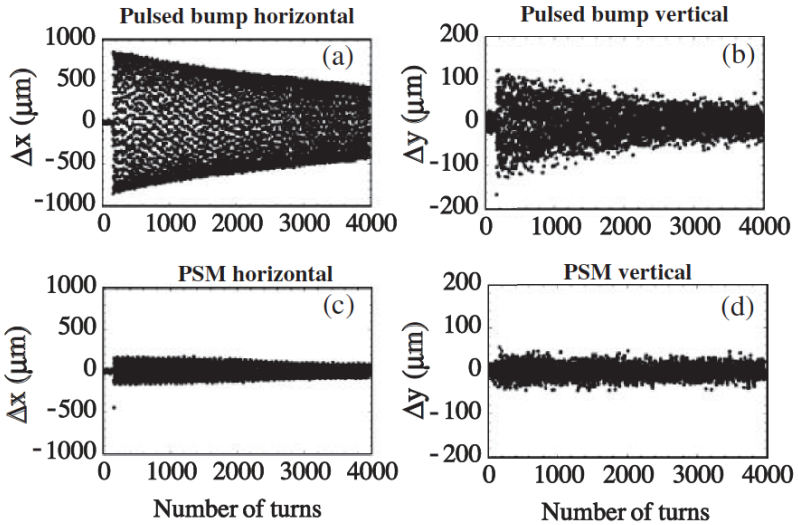
Pulsed sextupole injection

H. Takaki et al. PRSTAB 2010



- Using non-linear field for injecting while circulating beam remains unaffected
- Achieved stability of stored beam current <0.02%
- Coherent oscillations of stored beam greatly reduced
- Several light source upgrade projects consider it (MAXIV, Spring8,…)

Parameter	Value
Core length	300 mm
Bore diameter	66 mm
Number of coil turns	1
Integrated magnetic field at $x = 15$ mm	120 Gauss m
Peak current	3000 A
Inductance	4.3 μH
Pulse width	1.2 (2.4)[a] μs



Low Emittance Rings' Collaboration

- Common beam dynamics and technology issues for synchrotron light sources, linear collider damping rings and e+/e- colliders
- Formed a EU network within EUCARD2, started on 05/2013
  - Coordinated by CERN, INFN/LNF, JAI
  - Extended collaboration board including colleagues from US and Japan
  - 30 participating institutes world wide
  - First two network workshop with 70-80 participants @ Oxford (07/2013) and Soleil (01/2014)

- Next low emittance rings' technology workshop on 05-06/05/2014 at IFIC/Valencia
- FCCee study should profit from it!

Outlook

- Flux requirements are very close to SuperKEKB and fully compatible with CLIC injector (using SPS as a damping ring)
- Ramp rate confortable (can be increased to gain margin in flux requirements)
- First ideas for putting back leptons in already existing CERN injector complex
  - Co-habitation with the present (and future) LHC injectors is not given (impedance, super-cycle-sharing, new equipment,…)
- Top – up is challenging and should profit from synchrotron injection
  - Alternative injection schemes to be investigated, e.g. vertical injection (D. Talman)
- First ideas on injection elements (C. Bracco and B. Goddard)
- Profit from low emittance rings collaboration and synergy with other projects at CERN (CLIC, LHeC,…) and abroad (SuperKEKB, X-ray storage rings,…)

Lepton injector work units

J. Wenninger – FCC kick-off 2014

Lepton injectors
Overall design parameters
Baseline layout
Baseline parameters
Functional machine design
LEP chain performance and gaps
LEP chain compatibility with hadron injectors
New injector chain baseline
Technical systems
Low energy beam transfer lines
LIL/EPA re-installation feasibility
Existing injectors to be decommissioned for lepton operation
Technologies that require R&D
SuperKEKB-type injector option
CTF3 option usability
Planned LHeC test facility usability
Electron and positron sources