Alternate Injectors for a Higgs Factory

John Seeman
SLAC National Accelerator Laboratory
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CEPC-SppC Workshop

Topics

Present CEPC and FCCee Injectors

- Layouts
- Generic injection requirements

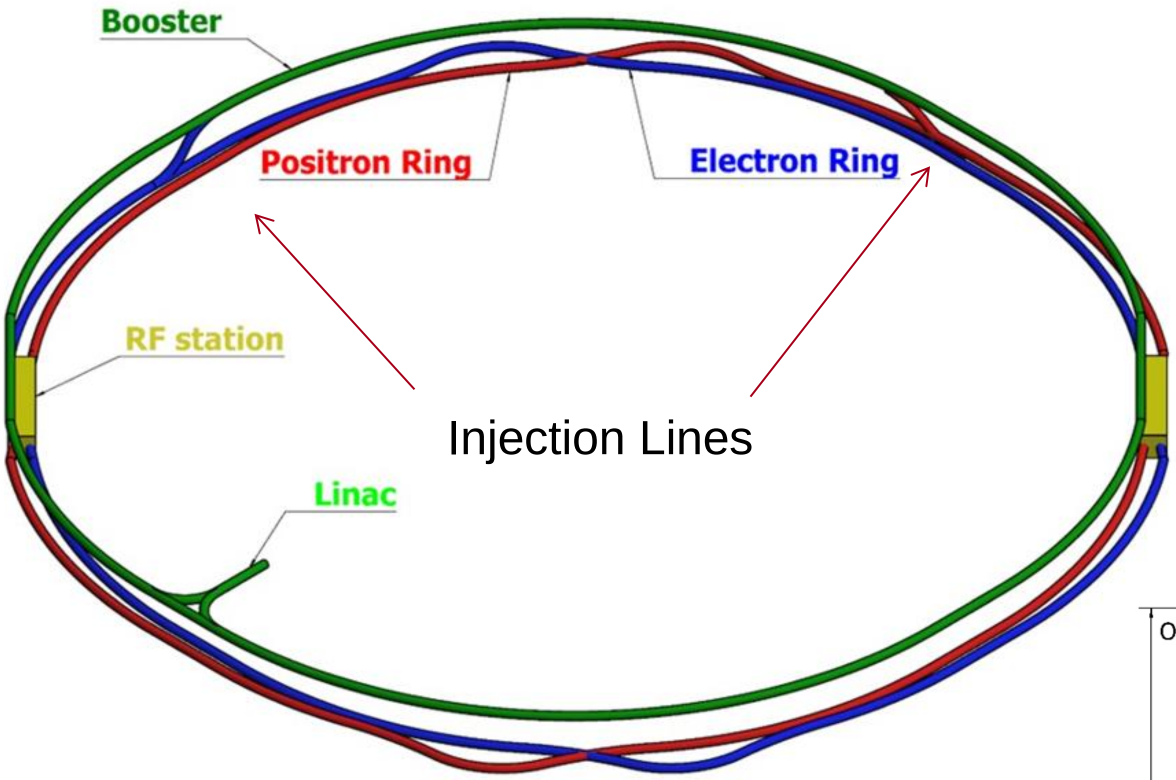
Alternate Injection Possibilities

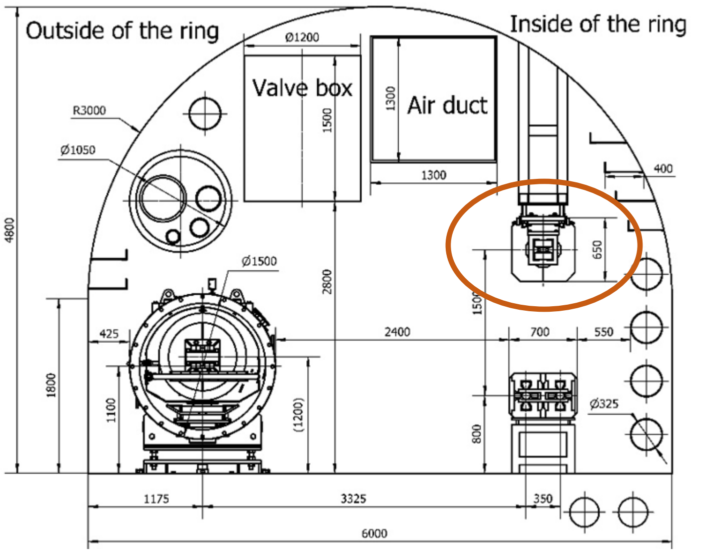
- Basic cost scaling

Design of a full energy PWFA or DWFA Injector

Proposed FACET-II two-stage Wakefield Test Module

Part 1: CEPC Tunnel Layout Showing Booster Location





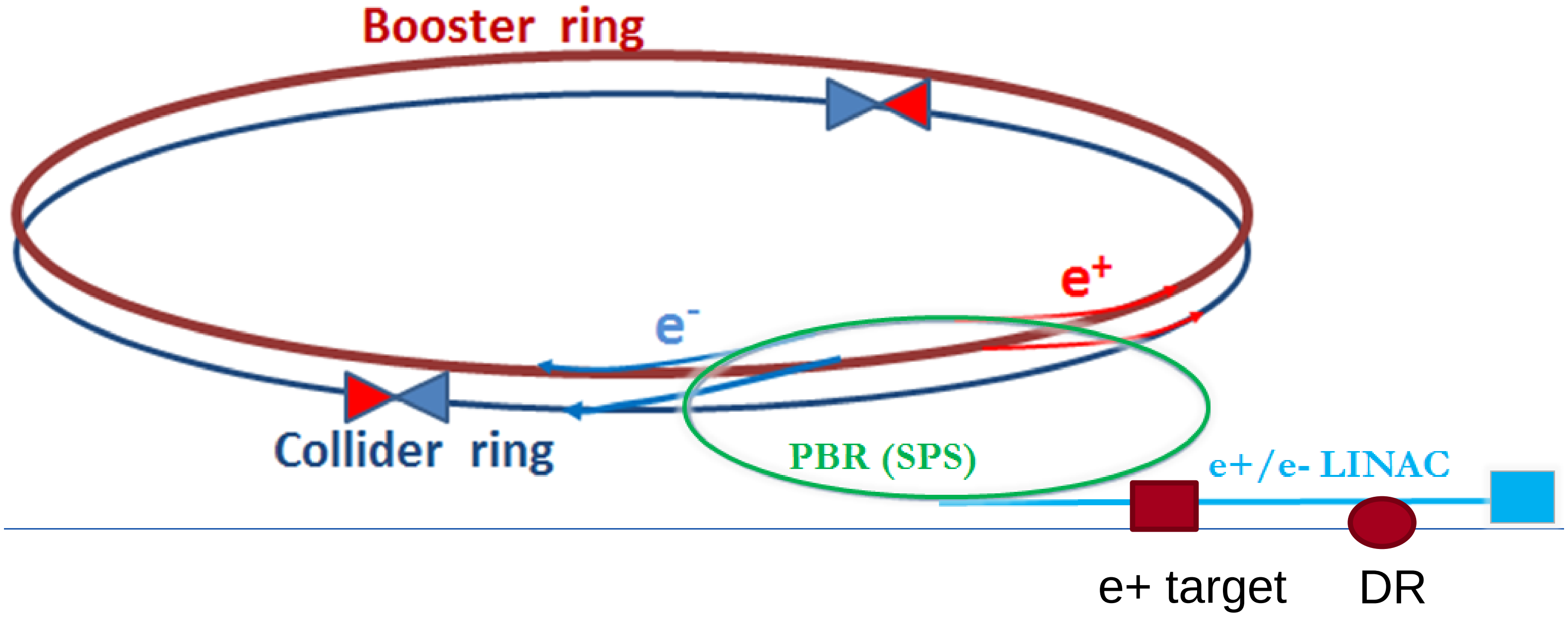
CEPC CDR Parameters showing Main Injection Requirements

	Higgs	*W*	*Z*
Number of IPs		2	
Energy (GeV)	120	80	45.5
Circumference (km)		100	
SR loss/turn (GeV)	1.68	0.33	0.035
Half crossing angle (mrad)		16.5	
Piwinski angle	2.75	4.39	10.8
N_e/bunch (10^{10})	12.9	3.6	1.6
Bunch number	286	5220	10900
Beam current (mA)	17.7	90.3	83.8
SR power /beam (MW)	30	30	2.9
Bending radius (km)		10.9	
Momentum compaction (10^{-5})		1.14	
β_{IP} x/y (m)		0.36/0.002	
Emittance x/y (nm)	1.21/0.0036	0.54/0.0018	0.17/0.0029
Transverse σ_{IP} (um)	20.9/0.086	13.9/0.060	7.91/0.076
ξ_x/ξ_y/IP	0.024/0.094	0.009/0.055	0.005/0.0165
V_{RF} (GV)	2.14	0.465	0.053
f_{RF} (MHz) (harmonic)		650 (217500)	
Nature bunch length σ_z (mm)	2.72	2.98	3.67
Bunch length σ_z (mm)	3.48	3.7	5.18
HOM power/cavity (kw)	0.46 (2cell)	0.32(2cell)	0.11(2cell)
Energy spread (%)	0.098	0.066	0.037
Energy acceptance requirement (%)	1.21		
Energy acceptance by RF (%)	2.06	1.48	0.75
Photon number due to beamstrahlung	0.25	0.11	0.08
Lifetime due to beamstrahlung (hour)	1.0		
Lifetime (hour)	0.33 (20 min)	3.5	7.4
F (hour glass)	0.93	0.96	0.986
L_{max}/IP (10^{34}cm^{-2}s^{-1})	2.0	4.1	1.0

FCCee Injector Complex

Injector complex is comprised by:

- e+/e- LINAC and Damping ring (up to ~6 GeV)
- Pre-Booster Ring - PBR (from ~6 to ~20 GeV)
- Booster ring (from ~20 to full FCCee energy)
- Proposal for extra ring with wigglers for rapid radiative polarization (@ ~1-2 GeV)



FCCee Collider Parameters (K. Oide, F. Zimmermann …)

Design		2017			
Circumference	[km]	97.750			
Arc quadrupole scheme		**twin aperture**			
Bend. radius of arc dipole	[km]	10.747			
Number of IPs / ring		2			
Crossing angle at IP	[mrad]	30			
Solenoid field at IP	[T]	± 2			
ℓ^*	[m]	2.2			
Local chrom. correction		y-plane with crab-sext. effect			
RF frequency	[MHz]	400			
Total SR power	[MW]	100			
Beam energy	[GeV]	45.6	80	120	175
SR energy loss/turn	[GeV]	0.036	0.34	1.72	7.80
Long. damping time	[ms]	414	76.8	22.9	7.49
Current/beam	[mA]	1390	147	29.0	6.4
Bunches/ring		70760	7280 (4540)	826 (614)	64 (50)
Particles/bunch	[10^{10}]	4.0	4.1 (6.6)	7.1 (9.6)	20.4 (26.0)
Arc cell		60°/60°	90°/90°		
Mom. compaction α_p	[10^{-6}]	**14.79**	7.31		
Horizontal tune ν_x		269.14	389.08		
Vertical tune ν_y		267.22	389.18		
Arc sext. families		208	292		
Horizontal emittance ε_x	[nm]	**0.267**	0.28	0.63	1.34
$\varepsilon_y/\varepsilon_x$ at collision	[%]	0.38	0.36	0.2	0.2
β_x^*	[m]	**0.15**	1 (0.5)		
β_y^*	[mm]	1	2 (1)		
Energy spread by SR	[%]	0.038	0.066	0.099	0.147
Energy spread SR+BS	[%]	0.073	0.072 (0.091)	0.106 (0.122)	0.193 (0.2[illegible])
RF Voltage	[MV]	**255**	696	2620	9500
Bunch length by SR	[mm]	2.1	2.1	2.0	2.4
Bunch length SR+BS	[mm]	4.1	2.3 (2.9)	2.2 (2.5)	2.9 (3.5)
Synchrotron tune ν_z		−0.0413	−0.0340	−0.0499	−0.0684
RF bucket height	[%]	3.8	3.7	2.2	10.3
Luminosity/IP	[10^{34}/cm^{2}s]	**137**	16.4 (30.0)	4.6 (8.0)	1.35 (2.09)

Injection issues

CEPC Injection Requirements (Linac into Booster)

SLAC

Parameter	Value	Unit
Beam Energy	10	GeV
Repetition rate	100	Hz
Bunch Charge	>1	nC
Energy Spread	<2E-3	
Emittance	< 0.3	mm.rad

Emittance is required by the vacuum chamber in the booster.
Bunch charge is required by the injection current in Higgs mode.

Booster Ring Injector is a Serious Accelerator!

The 100 km booster is a large accelerator with some complicated technologies but overall is mostly conservative.

Issues include :

100 km of complex accelerator components
The booster has more than 2.2 to 10 GeV of SC RF at high power with significant HOMs.
Vacuum chamber issues are modest (SR, eddy currents, heat expansion).
Low field dipole magnet strength (~60 gauss) has issues at 6-10 GeV but fewer at 20 GeV.
Tunnel interferences with collider components (e.g. SCRF, detectors, cryo-distribution)
Potential unintended cross talk to e+e- or pp colliders including radiation.
Beam instabilities at 6-10 GeV could spray radiation on the other accelerators and hardware.
→High cost at 100 km.

Parametric Cost Analysis

The plan is to provide an average parametric cost value for each segment of the injector chain.

The costs are split into “tunnel” and “accelerator” costs.

A cost value per meter were be assigned depending on the difficulty of the technology.

For example, a linac costs more per meter than a transport line. Curved transport more than straight. SC linac is more than Cu.

A linac tunnel cost more per meter than a transport line tunnel because of waveguides, klystrons, and modulators.

When an accelerator shares a tunnel with another accelerator, the main accelerator get the cost of the tunnel and only the incremental costs for the tunnel will be added to the lesser one.

The cost is then calculated by the cost per meter times the length of the accelerator segment.

→ The cost values are only for comparisons of different technologies and do not represent the actual real costs which is more complicated to calculate.

Various 125-175 GeV Injector Types Compared (Parametric)

SLAC

Base injector at 100 Hz:

(=6 GeV linac+DR+gun+target+injection into the collider rings) (same for all and not included)

	Relative parametric cost
Booster (FCCee) (baseline)(175 GeV)	1.0 (Nominal)
Booster (CEPC)(baseline) (125 GeV)	0.9
Full Energy Cu linac (175)	1.2
e- Beam Plasma Wake Field Accelerator PWFA (175)	0.4
e- Beam Dielectric Wake Accelerator DWA (175)	0.38
Laser Wake Field Accelerator LWFA (175)	30.0
e- CLIC (classic) style linac (175)	0.7
Awake (proton driver) PWFA	Need ~100 SPSs for 100 Hz rate with 10bpp

Hogan: SLAC Linear Collider Concept in 2014 using PWFA

SLAC

Proceedings of IPAC2014, Dresden, Germany THPRI013

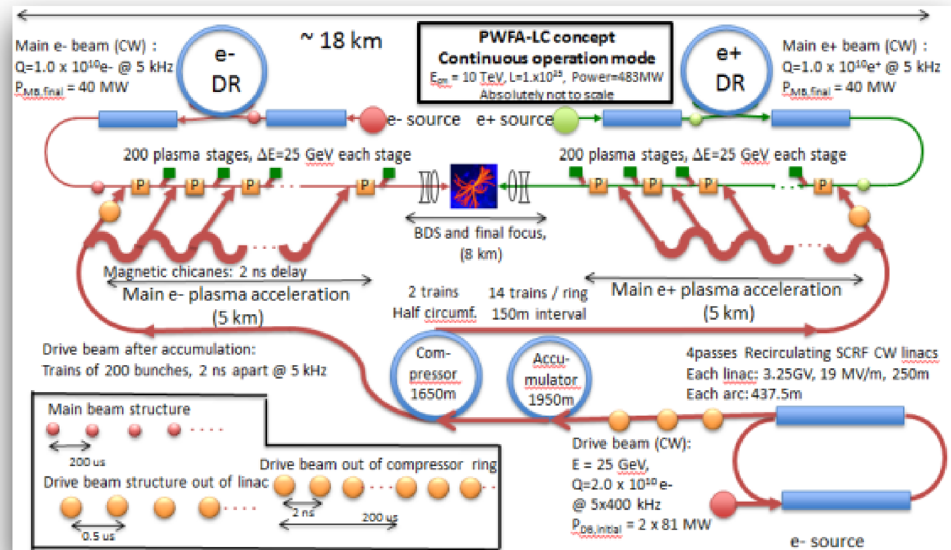
SLAC-PUB-15426
http://arxiv.org/abs/1308.1145
E. Adli *et al*, IPAC14

A BEAM DRIVEN PLASMA-WAKEFIELD LINEAR COLLIDER FROM HIGGS FACTORY TO MULTI-TEV*

J.P. Delahaye, E. Adli, S.J. Gessner, M.J. Hogan, T.O. Raubenheimer, SLAC,
W. An, C. Joshi, W. Mori, UCLA

Table 1: Major PWFA-LC beam parameters

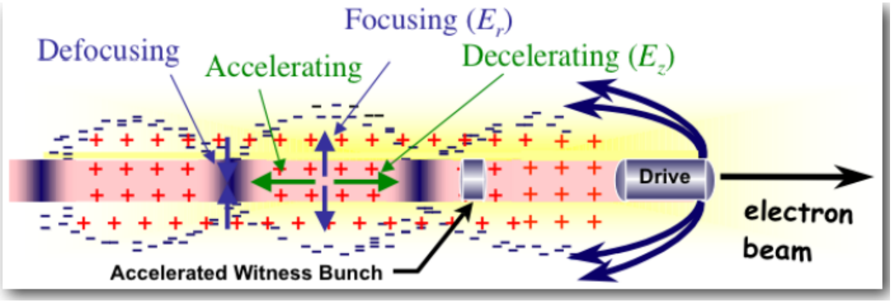
Colliding beam energy, CM	GeV	250	500	1000	3000	10000
N, experimental bunch		1.0E+10	1E+10	1.0E+10	1.0E+10	1.0E+10
Main beam bunches / train		1	1	1	1	1
Main beam bunch spacing,	nsec	3.33E+04	5.00E+04	6.67E+04	1.00E+05	2.00E+05
Repetition rate,	Hz	30000	20000	15000	10000	5000
n exp.bunch/sec,	Hz	30000	20000	15000	10000	5000
Beam power / beam at IP	W	6.0E+06	8.0E+06	1.2E+07	2.4E+07	4.0E+07
Effective accelerating gradient	MV/m	1000	1000	1000	1000	1000
Overall length of each linac	m	125	250	500	1500	5000
BDS (both sides)	km	2.00	2.50	3.50	5.00	8.00
Overall facility length	km	2.25	3.00	4.50	8.00	18.00
Drive beam						
Transfer efficiency drive to main	%	50	50	50	50	50
Drive beam power per beam	MW	12.2	16.2	24.3	48.6	81.0
Drive beam acceleration efficiency	%	39.9	42.0	44.3	45.0	45.3
Main beam acceleration efficiency	%	19.9	21.0	22.1	22.5	22.7
Wall plug to main beam efficiency	%	9.1	10.8	13.1	16.1	17.0
Total wall plug power	MW	132.9	150.4	185.5	301.3	477.9
IP Parameters						
Normalized horizontal emittance	m	1.00E-05	1.00E-05	1.00E-05	1.00E-05	1.00E-05
Normalized vertical emittance	m	3.50E-08	3.50E-08	3.50E-08	3.50E-08	3.50E-08
Horiziontal beam size at IP (1σ)	m	6.71E-07	4.74E-07	3.35E-07	1.94E-07	1.06E-07
Vertical beam size at IP (1σ)	m	3.78E-09	2.67E-09	1.89E-09	1.09E-09	5.98E-10
Bunch length at IP (1σ)	m	2.00E-05	2.00E-05	2.00E-05	2.00E-05	2.00E-05
Disruption parameter, Y		8.44E-02	2.39E-01	6.75E-01	3.51E+00	2.14E+01
delta_B	%	2.75	6.66	12.76	23.10	29.88
ngamma		0.57	0.73	0.88	1.05	1.14
Geometric Lum ($cm^{-2} s^{-1}$)		9.41E+33	1.25E+34	1.88E+34	3.76E+34	6.27E+34
Total Luminosity ($cm^{-2} s^{-1}$)		1.57E+34	2.09E+34	3.14E+34	6.27E+34	1.05E+35
Luminosity in 1% top energy ($cm^{-2} s^{-1}$)		9.41E+33	1.15E+34	1.57E+34	2.51E+34	3.14E+34
Fig. merit:Luminosity/wall plug (10^{31}/MW)		11.8	13.9	16.9	20.8	21.9



- ‘Cold’ Drive Linac
- 100μs bunch spacing
- Tricky delay chicanes

SLAC FACET has accelerated both e- and e+

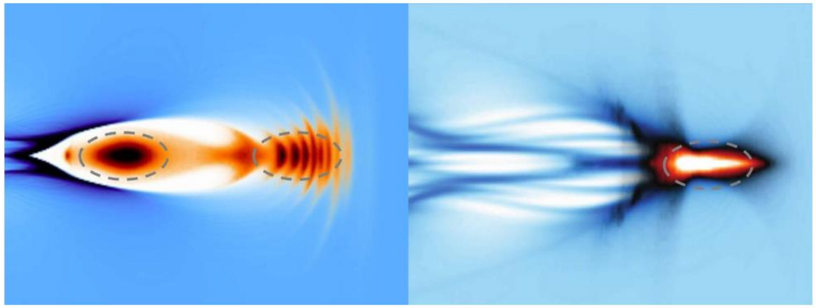
Electrons



Positrons
(Hollow plasma)

Instead of using two separate particle bunches – one to create a wake and the other to surf it – the team discovered that a single positron bunch can interact with the plasma in such a way that the front of it generates a wake that both accelerates and focuses its trailing end. This occurs after the positrons have traveled about four inches through the plasma.

"In this stable state, about 1 billion positrons gained 5 billion electronvolts of energy over a short distance of only 1.3 meters," said former SLAC researcher Sébastien Corde, the study's first author, who is now at the Ecole Polytechnique in France. "They also did so very efficiently and uniformly, resulting in an accelerated bunch with a well-defined energy."

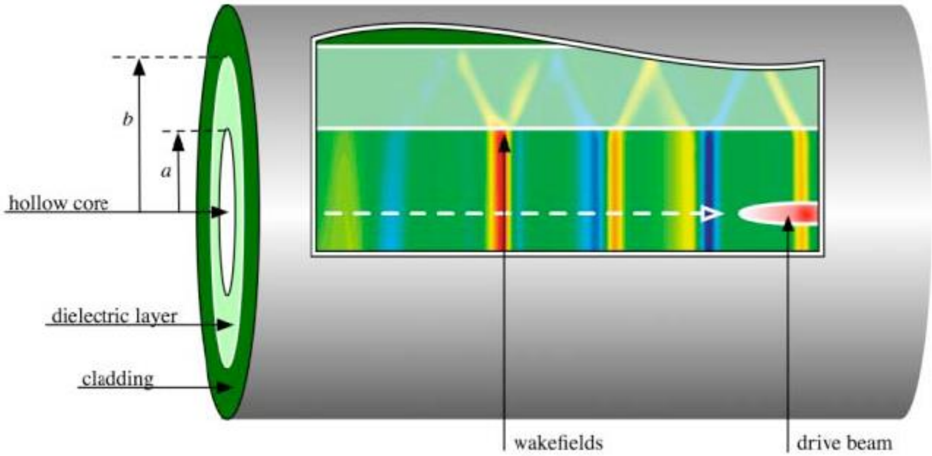


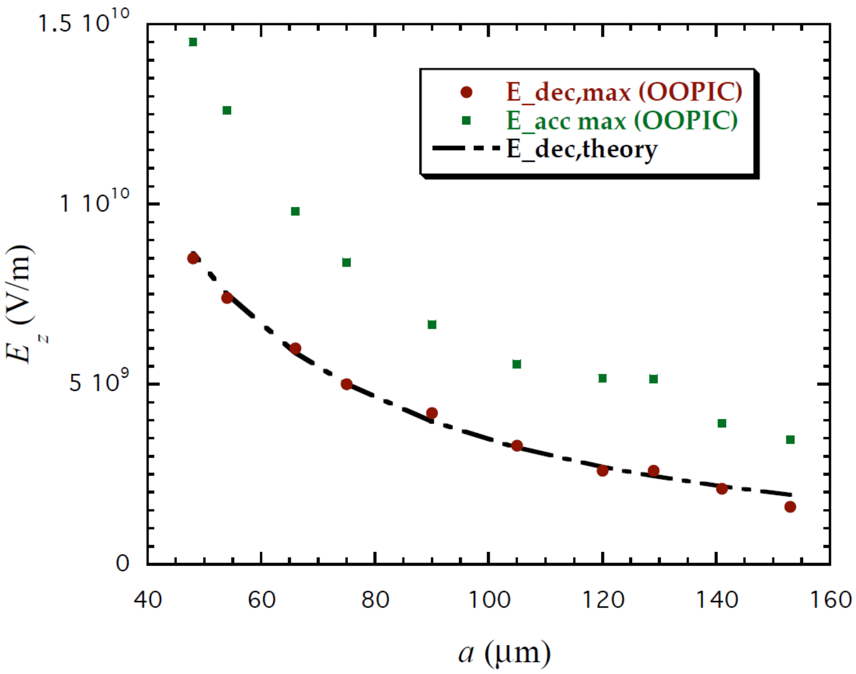
Achieved parameters:

$3x10^{10}$ drive bunches
Drive bunch length of ~40 microns
3 m plasma cells,
$3x10^{16}$ plasma density,
10 GeV/m,
10 GeV/stage
Transformer ratio = 1, but try for higher

Dielectric Wake Accelerator (O'Shea)

Hollow ceramic tubes with metal outer jacket.





If a= 150 microns and b = 200 microns = 2.8 GeV/m

If a= 225 microns and b = 320= microns = 1.0 GeV/m

DWA Parameters Achieved (~2005)

Parameter	Short Pulse	Long Pulse
Beam Energy	25 GeV	
Beam Charge	3 nC	5 nC
Energy Spread (FWHM)	< 2% (0.6 GeV)	< 0.28% (0.070 GeV)
Beam Length (σ_ζ)	≥20 µm	≤150 µm
Beam Radius (σ_ρ)	<10 µm	
In. Dielec. Rad., a	100 µm	
Out. Dielec. Rad., b	175 µm	
Dielec. Perm., ε	~ 3	
Dielec. Length, L_d	10 cm	
Peak E_z, acc.		1.1 GV/m
Peak $E_{r,surface}$		2.2 GV/m
Max. Gain (10 cm)		0.11 GeV

Need 15 to 30 m long cells to reach 30 GeV gain

PWFA and DWA Injector (Simplified)

Electrons:

Make six bunches longitudinally placed at 30 GeV each from a low emittance gun at a few x 10^{10} e- each

1.6 m (5.7 nsec) bunch separation longitudinally

→ One witness (injected bunch per cycle into CEPC/FCCee) and five drive bunches

Positrons:

e+ bunch from the damping ring accelerated to 30 GeV

Make five e- bunches at 30 GeV each a few x 10^{10}

→ One e+ witness (injected bunch into CEPC/FCCee) and five drive bunches

Lasers:

→ Only pre-ionize gas with lasers with no energy put into the beam. (perhaps could do without.)

Acceleration scheme:

Five PWFA or DWA cells at 30 GeV each to reach 180 GeV, per beam

Schematic of Beam PWFA or DWA Injector (Not Optimized)

One Linac makes a witness bunch and several drive bunches (~5) longitudinally and then sequentially use then to accelerate the witness bunch by 30 GeV per PWFA or DWA cells to get to 175 (180) GeV.

Need to longitudinal (phase) slip the drive bunches so that all will catch up with the "witness" bunch that gets accelerated and ultimately injected into one of the main rings.

Need longitudinal distance slips of 1.0 m to 1.5 m (bunch spacing) which is about the distance between acceptable, with reduced transverse wakes, linac buckets.

$$\Delta z = \theta * \Delta r$$

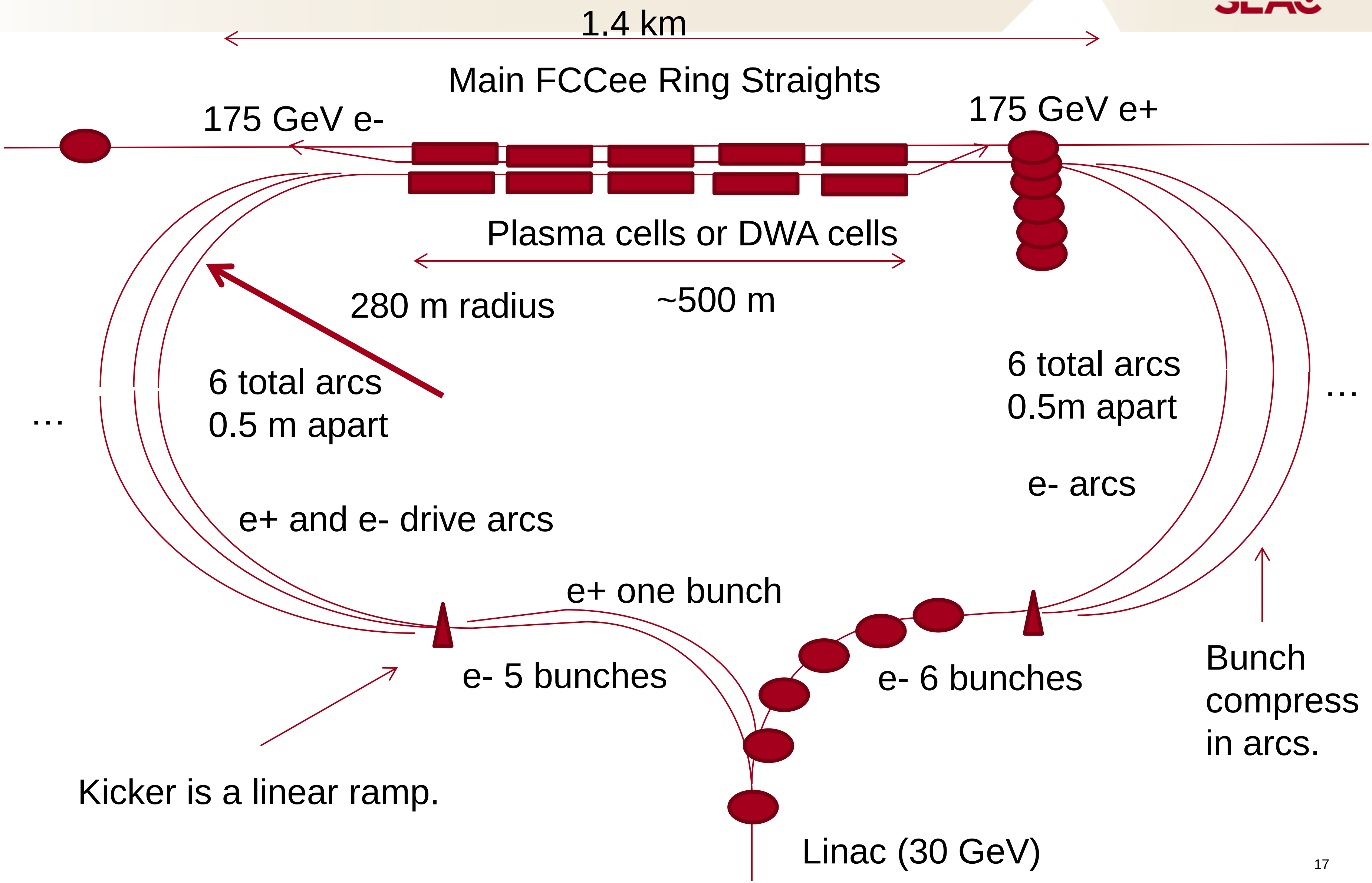
for example $\Delta z = 1$ m and $\Delta r = 1$ m→ $\theta = 1$ rad

Option 1: Do the phase slipping in the CEPC/FCCee main ring tunnel: then $\Delta z \sim 16{,}000$ m. Way too long!

Option 2: Do the phase slipping in a separate tunnel $\rho = 280$ m (like SLAC SLC),
$\theta = \pi$ for $\Delta r = 0.5$ m gives $\Delta z = 1.57$ m , Length ~ 879 m. Perfect!

Emittance growth at 30 GeV is small with SLC style lattice.

PWFA or DWA Overview



Design very similar to the SLAC SLC Arcs (1988-1998)

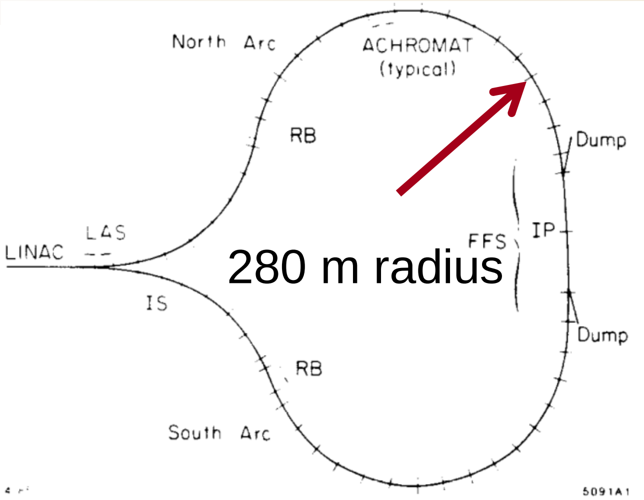


Fig. 3. Layout of Arcs in the horizontal plane.

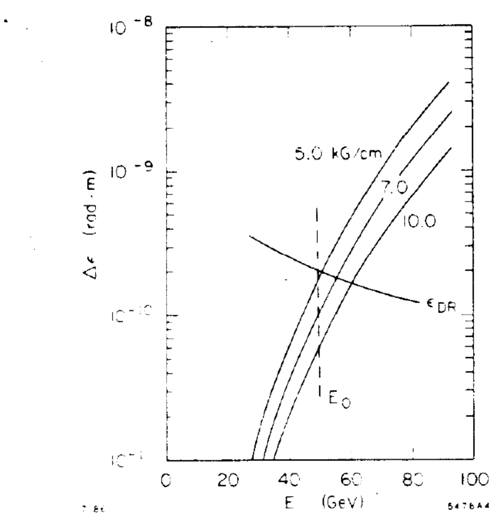
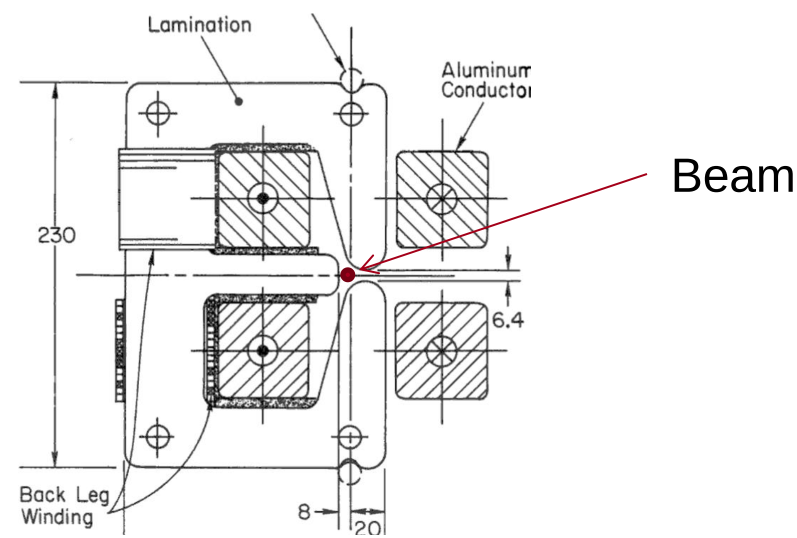


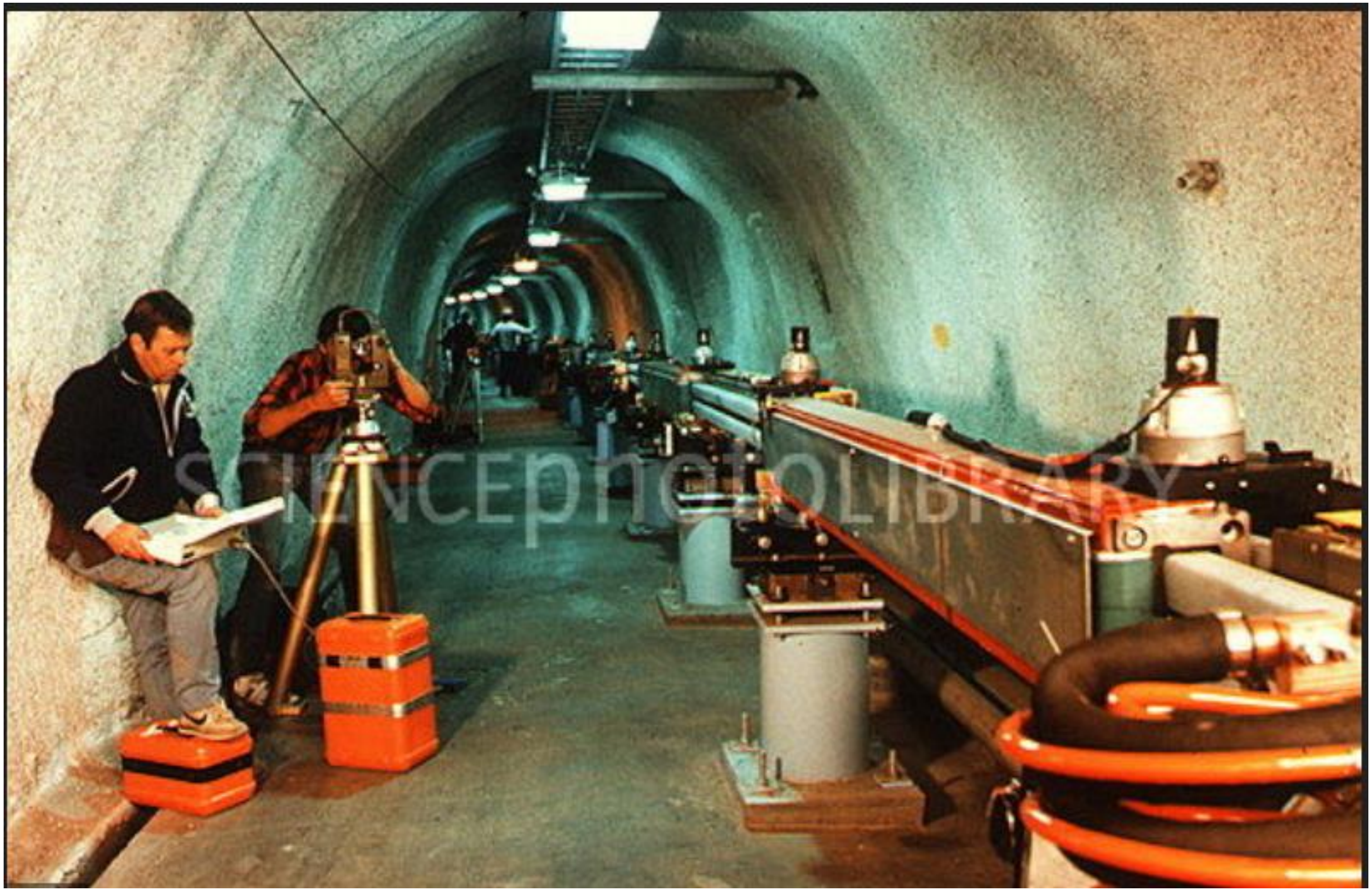
Fig. 1. Beam emittance growth as a function of the beam energy for the gradient values 5.0, 7.0 and 10.0 kGauss/cm. Also is shown the curve for ideal damping ring emittance scaled to the linac energy. The dashed

TABLE I

Dipole Field in KGauss	B_{y0}	= 5.96976
Bending Radius in Meters	ρ	=279.378
Field Index	n_f	=-32847.5
	n_d	=+32848.5
Field Gradient KG/cm at Equil. Orbit	g_{av}	=7.0189
Sextupole Terms:	B_s	$=1/2g'x^2$
in focusing magnet:		
	$\frac{g\rho}{\rho'}$	=+0.0013579 m
	g'	=-1.629 kG/cm
in defocusing magnet:		
	$\frac{g\rho}{\rho'}$	=-0.0022748 m
	g'	=-2.702 kG/cm
Eff. Arc Length of Magnet ℓ	L_b	=2.50300 m
	L_g	=2.48565 m
	iron L	=2.47935 m
1/2 cell arc length		2.596201936 m
Total Arc Cell Length		5.192402112 m
		=17.03544 feet
12 Cell Bend Angle		0.513323348°



SLAC SLC Arc Installation



Optimum Number of Arcs (Bunches)

$$E_f = E_0 + n\,\Delta E_c$$

E_f = final energy = 175 to 180 GeV
E_0 = linac energy
ΔE_c = PWFA cell incremental energy
n = number of PWFA cells
n+1 = number of arc transport lines (each side)

E_0 (GeV) (Linac)	n	ΔE_c (GeV) (PWFA)
44	3	44
35	4	35
30	5	30
25	6	25
22	7	22

Accelerating Cells

For PWFA length:

$3x10^{16}$ plasma density, 3 m long → 30 GeV each

For DWA:

If a= 200 microns (radius) and b = 300= microns = 1.0 GeV/m →30 m → 30 GeV (It will be shorter if smaller diameter.)

Advantage: Beam sees no direct material.

Rough Hardware of a PWFA/DWFA Injector

Need more Cu linac over base linac = 24 GeV (30-6 GeV):

Need to build 12 transport lines (six per side): 12 lines x 1100 m/line =13 km

Need to build 10 Plasma or DWA cells (5 per side)

What is Next for [CEPC/FCCee] Injector Design using PWFA or DWA

Optimize number of cells.

Linac parameters to make 6 (or n) good bunches.

Bunch length manipulation.

Define arc layout.

Define optics entering and leaving the plasma and dielectric cells.

Beam tolerances in transport and accelerating cells.

An Aside: Why a PWFA or DWA Injector?

Large overall cost savings are expected for CEPC/FCCee if this injector works!

However, the big view:

Jumping into a full 1 TeV scale linear collider using PWFA or DWA is a very big step from the present status. Many technologies have to work. Need to prove the basic technologies are viable and reliable.

A 125-175 injector for CEPC/FCCee with less stringent parameters would be an excellent first step. Most of the technologies will then be proven for a high energy linac collider.

First→ Test at FACET-II!

(New) Proposed Beam Test of a two stage PWFA (+DWA) at SLAC

First:

Complete FACET-II.

Next:

Add a two stage PWFA (and/or DWA) experiment modules.

Try for 30 GeV result starting from 10 GeV bunches at 30 Hz.

Plan:

Make two e- bunches (both with 3×10^{10}) in the linac spaced 5.7 nsec (1.76 m) apart.

First bunch self accelerates its tail (witness) in first plasma cell (few $\times 10^{9}$) from 10 to 20 GeV.

Second bunch accelerates the same witness bunch to 30 GeV in second plasma cell.

Measure properties of 30 GeV final witness beam.

Goal: Test Beam Parameters similar to CEPC/FCCee

Two PWFA or DWA stages: 10GeV start + 2 x 10GeV cells = 30 GeV (final)

Goal for output beam parameters (needed for CEPC/FCCee):

30 Hz

30 GeV

Charge per exiting bunch ~ 6 x 10^9

Charge stability < 2%

Bunch length < 2 mm

Energy spread rms < 0.5 %

Emittance (x,y) < 10 nm-rad

Energy stability < 1 %

Transformer ratio =1.0+

Transverse wakes in SLAC Cu linac for the two bunches

Longitudinal:

The longitudinal wakes are compensated by running the bunches in the Cu linac slightly off crest in the SLED pulse as was done in the SLC. Besides, if the three bunches have somewhat different energies in Sector 20 they can be compensated by adjusting the three transport lines. Different energies may help with transverse wakes.

Tranverse:

Karl Bane has calculated the transverse wakes following a leading bunch. SLAC-PUB-14608 (Dec. 2011). Concluded that 5 nsec spacing is the best. 2.5 nsec worst.

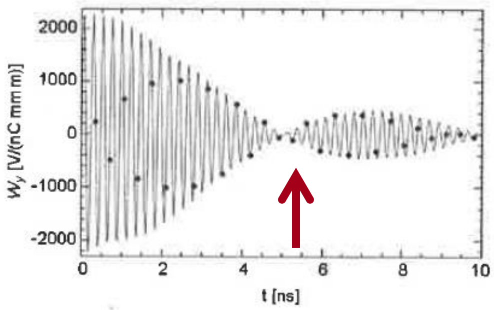


Figure 2: Long-range dipole wake of SLAC linac structure over two time ranges, with the bucket locations indicated by the red dots (lower figure).

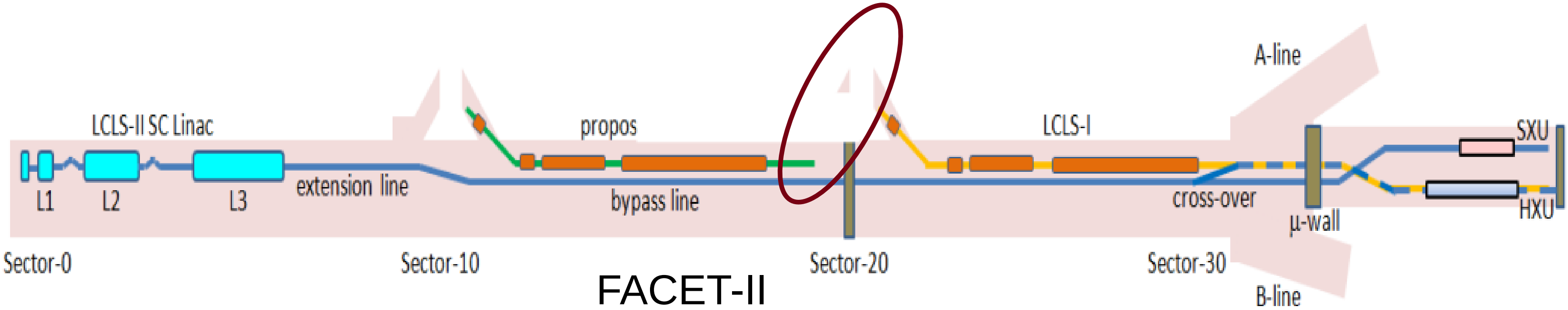
Decker and Sheppard have been studying transverse wakes with two LCLS bunches at 150 pC. Concluded that with carefully adjusted linac transverse bumps, the linac transverse bunches can be compensated with any bunch spacing at 150 pC. (Similar to what Seeman and Decker did for the SLC in ~1990.)

If these do not work then fall back to only 2 drive bunches spaced by 5 nsec or reduce bunch charges.

Plotted (early) path difference is 1.76 m which is 5.86 nsec. → Good distance.

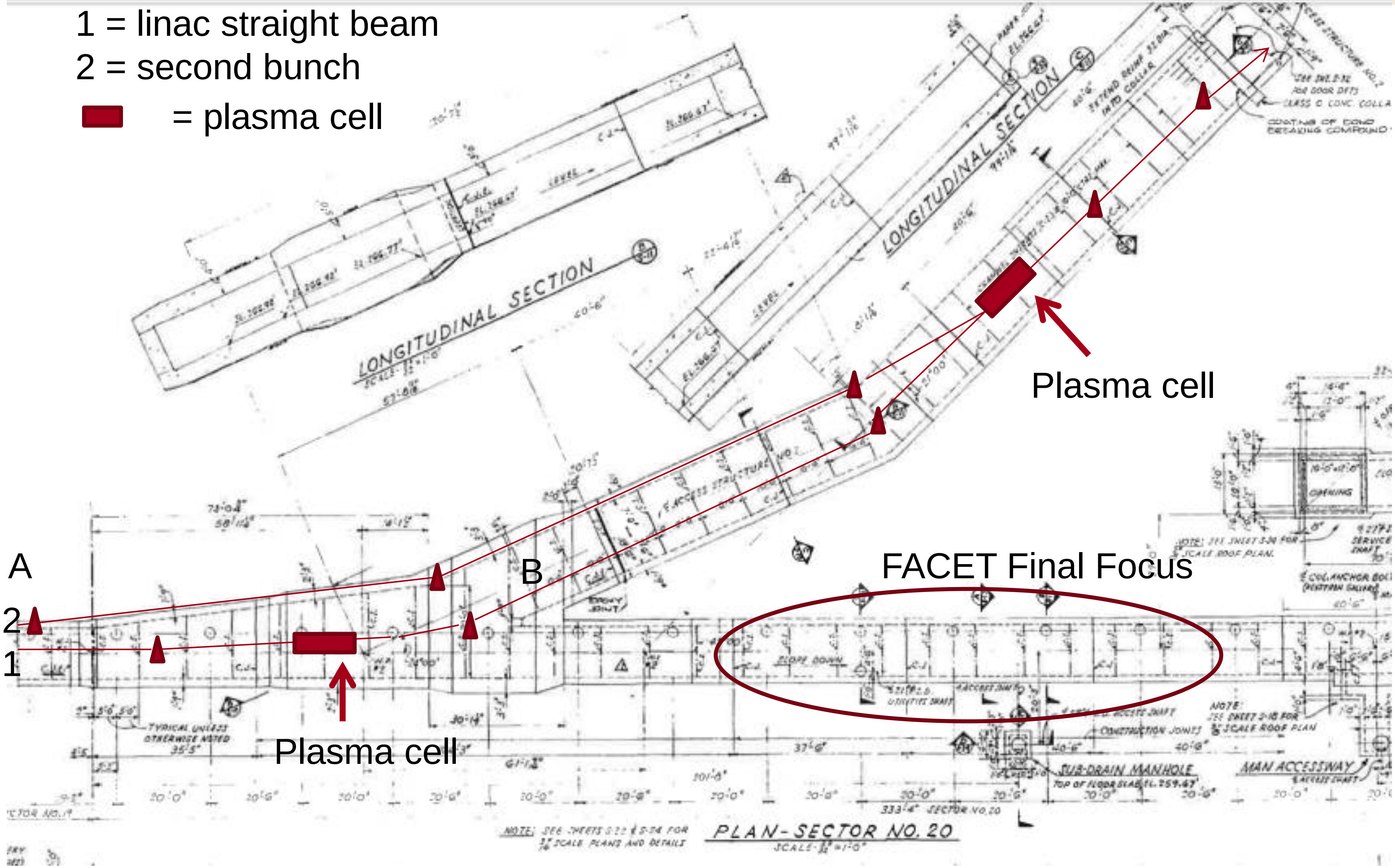
Rough Layout of SLAC Linac showing FACET-II Area

PWFA-DWA test will happen here, if approved.

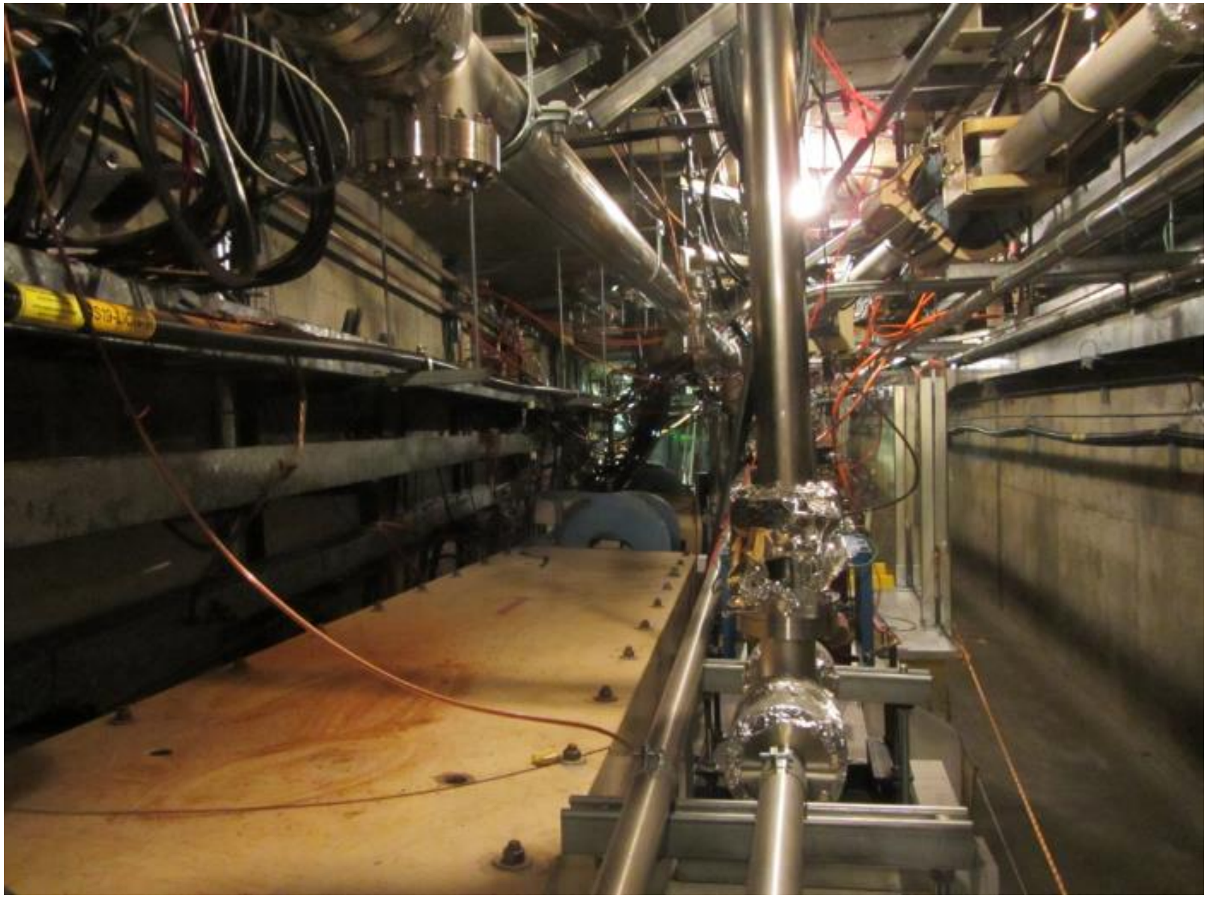


FACET-II

Schematic horizontal trajectories of two bunches (plan view)



Six present beam lines in Sector 20 at “A”

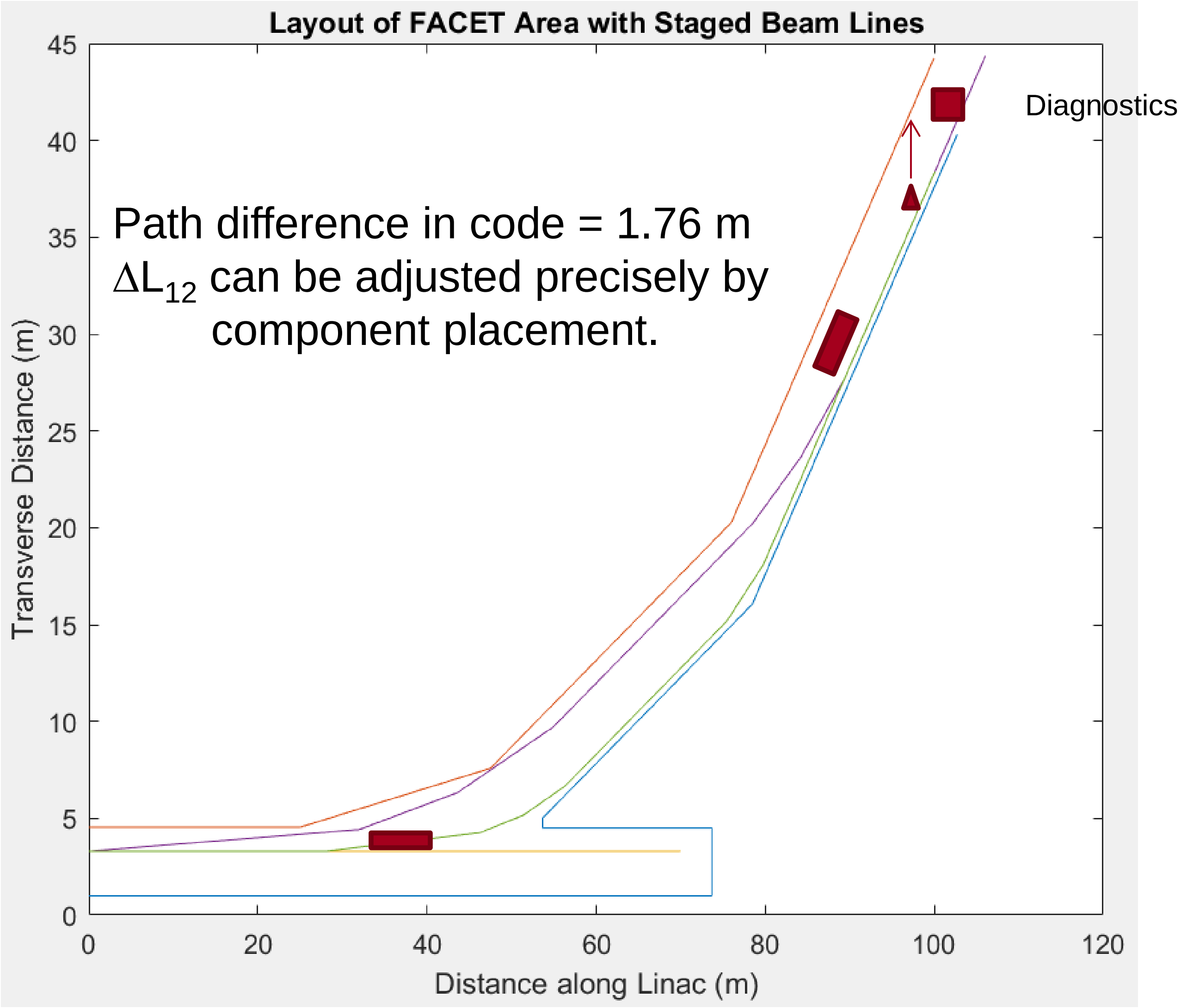


Sector 20 Adit in the tunnel at “B”

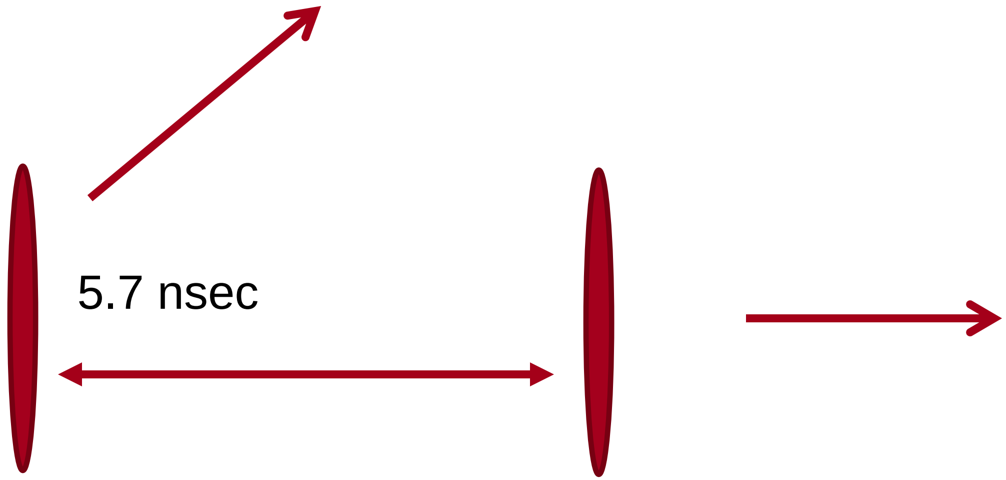
FACET-II

Extraction line to positron source

MATLAB: Exact FACET Area including Two Beam Lines

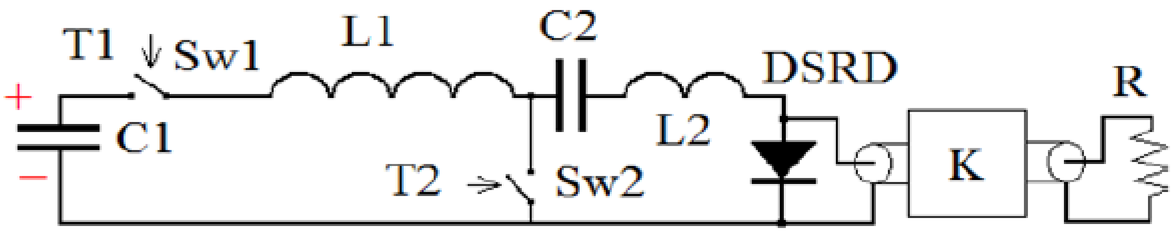


One kicker will change trajectories of second drive bunch



Present kicker has ~25 nsec rise time.

2 nsec Fast kicker (A. Krasnykh et al, SLAC)



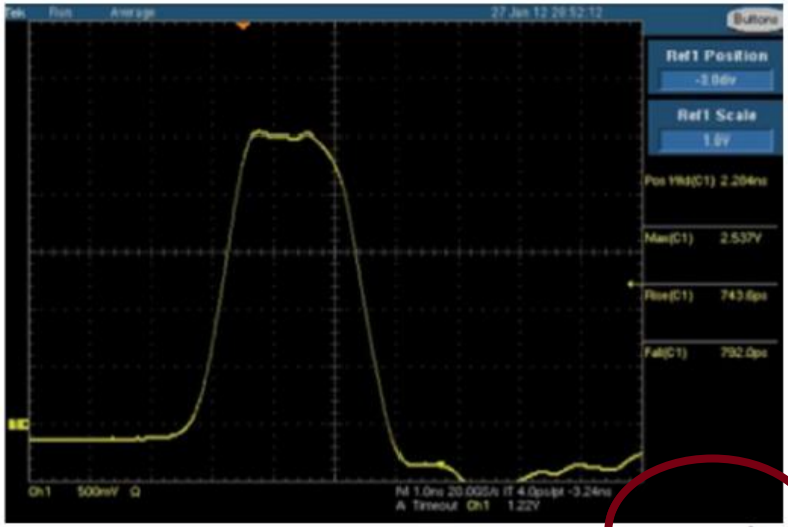


Figure 24: Waveform resulting from a single DSRD crystal. Horizontal scale is 1 nsec/div

SLAC FACET-II PWFA/DWA Test: Future work if approved:

PWFA:

Find the optimum plasma cell parameters.
Arrange plasma/drive parameters to make small witness energy spread.

Beams:

Fine tune beam lines 1 and 2 for paths to the correct length to about 10 microns and be able to tune to these values.
Make beam optics for all beam line transitions to and from plasma cells.
Determine if dipole bends (use segments of SLC arc magnets) can preserve emittances
Investigate tolerance in beam transport (SR, CSR, …)
Work out drive beam dumps.
Work out the longitudinal beam loading and linac RF phases in the Cu linac.
Plasma cell parameters
See if linac bumps can fix transverse wakes in Cu linac at 5.6 nsec.
Can the FACET-II gun make two 2-4 x 10^{10} bunches?
Make a full scale 4 nsec rise time fast kicker.

Thanks for your attention

Inputs from:

K. Bane, J. Sheppard, F-J. Decker (SLAC linac wakes)

X. Cui (CEPC Injection)

W. Chou, J. Gao (CEPC)

M. Hogan (PWFA)

S. Ogur, K. Oide, F. Zimmermann (FCC, injection, costs)

B. O’Shea (DWFA)