Injection Topics for Tau-Charm Factories

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Topics

- Tau-Charm collider parameters
- Injection requirements
- Injection into the rings
- Optimum injector
  - Linac layout
  - Tunnel length
  - Damping rings
  - Transport lengths
- Minimum costs
  - Straight linac
  - Folded linac
  - Recirculating linac
  - Rapid cycling synchrotron and low energy linac
- Conclusions

Thank you for Injection Input

China (Hefei):

- Q. Luo (Injection)
- D. Xu (Sources)

China (IHEP):

- X. Zhang (CEPC Injection)

Frascati (INFN):

- M. Biagini (Ring injection)
- R. Boni (Linacs)

Japan (KEK):

- A. Akai (Linac issues and costs)
- M.Tobiyama (SuperKEKB feedback)

Russia (BINP, Dubna)

- A. Bogomyagkov (Rings)
- E. Levichev (Lattices and injection)

Switzerland (CERN):

- S. Ogur (FCC injection)
- K. Oide (FCC lattice)
- F. Zimmermann (FCC Injection, LEP costs)

US (SLAC):

- F-J. Decker (SLAC linac)
- J. Sheppard (PEP-II Injection)
- U. Wienands (Top-up ring issues)

Tau-Charm Beam Requirements for Injection

Maximum fill time from zero current < 15 minutes

Charge per injected bunch ~ 2 to 50 x 10^9

Charge stability < 2%

Bunch length < 2 mm

Energy spread rms < 0.5 %

Emittance (x,y) < 10 nm-rad

Energy stability < 1 %

Injection Goals

All the injectors that are discussed are single bunch injectors [but could be upgraded 2 to 10 bunches per pulse]

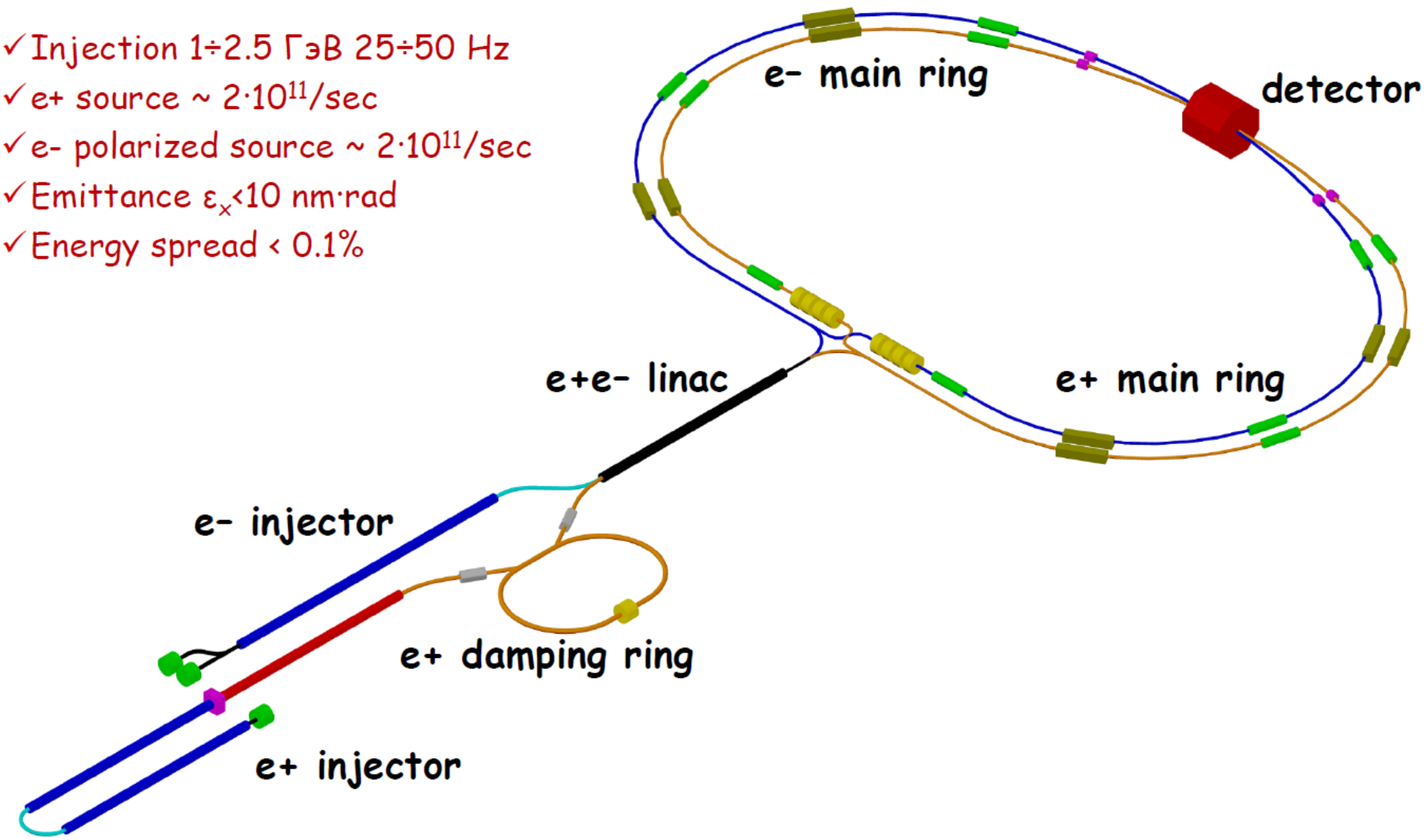
For T-C need to fill the maximum number of bunches at 1.5 to 3 GeV

Need to fill from scratch and in top-up mode.

In top up mode: Number of injection pulses with quanta of ~10 to 20 % of full charge per bunch (1x 10^9).

BINP Tau-Charm (2018) (Bogomyagkov)

- ✓Injection 1÷2.5 ГэВ 25÷50 Hz
- ✓e+ source ~ $2\cdot10^{11}$/sec
- ✓e- polarized source ~ $2\cdot10^{11}$/sec
- ✓Emittance ε_x<10 nm·rad
- ✓Energy spread < 0.1%



NSLS-II Injection Stacking

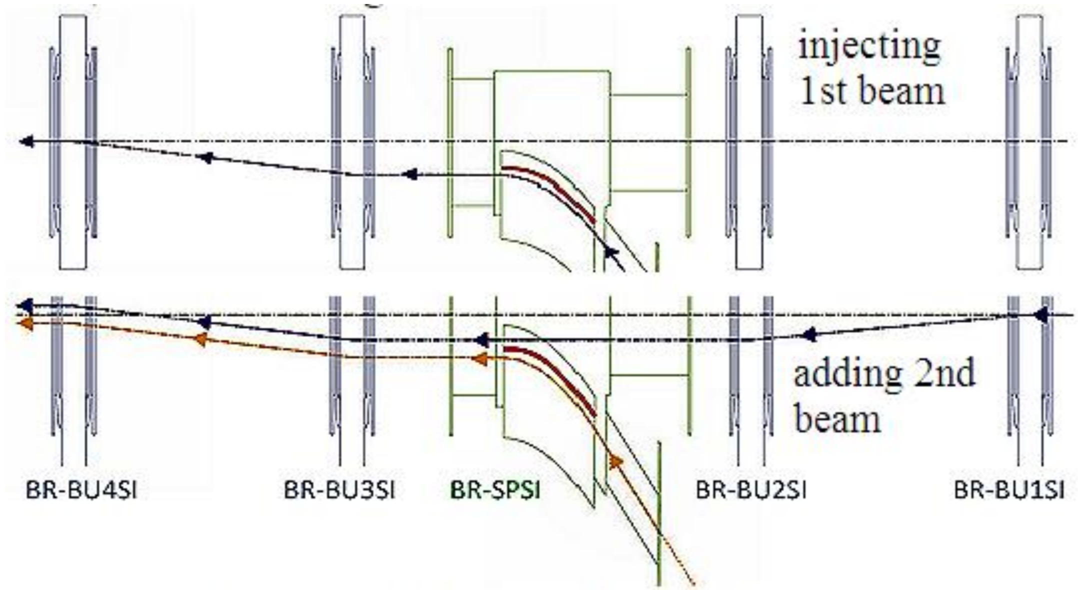


Figure 3: Beam-stacking schematics.

For charge exchange, inject bunch on axis and remove stored bunch.

BINP Tau-Charm Parameters (2018)

Energy	1.0 GeV	1.5 GeV	2.0 GeV	2.5 GeV
Circumference	813.1 m			
Emittance hor/ver	8 nm/0.04 nm @ 0.5% coupling			
Damping time hor/ver/long	50/50/25 ms	30/30/15 ms		
Bunch length	21 mm	12 mm	10 mm	10 mm
Energy spread	$8.7 \cdot 10^{-4}$	$11 \cdot 10^{-4}$	$9.3 \cdot 10^{-4}$	$7.2 \cdot 10^{-4}$
Momentum compaction	$8.73 \cdot 10^{-4}$	$8.81 \cdot 10^{-4}$	$8.82 \cdot 10^{-4}$	$8.83 \cdot 10^{-4}$
Damping wiggler field	50 kGs	50 kGs	35 kGs	10 kGs
Synchrotron tune	0.007	0.012	0.009	0.008
RF frequency	499.95 MHz			
Harmonic number	1356			
Particles in bunch	$7 \cdot 10^{10}$			
Number of bunches	406 (10% gap)			
Bunch current	4.2 mA			
Total beam current	1.7 A			
Beam-beam parameter	0.135	0.135	0.121	0.097
Luminosity	$0.6 \cdot 10^{35}$	$0.9 \cdot 10^{35}$	$1.0 \cdot 10^{35}$	$1.0 \cdot 10^{35}$

Total N = ~3x 10^{13}

BINP Electron Injector (Polarized)

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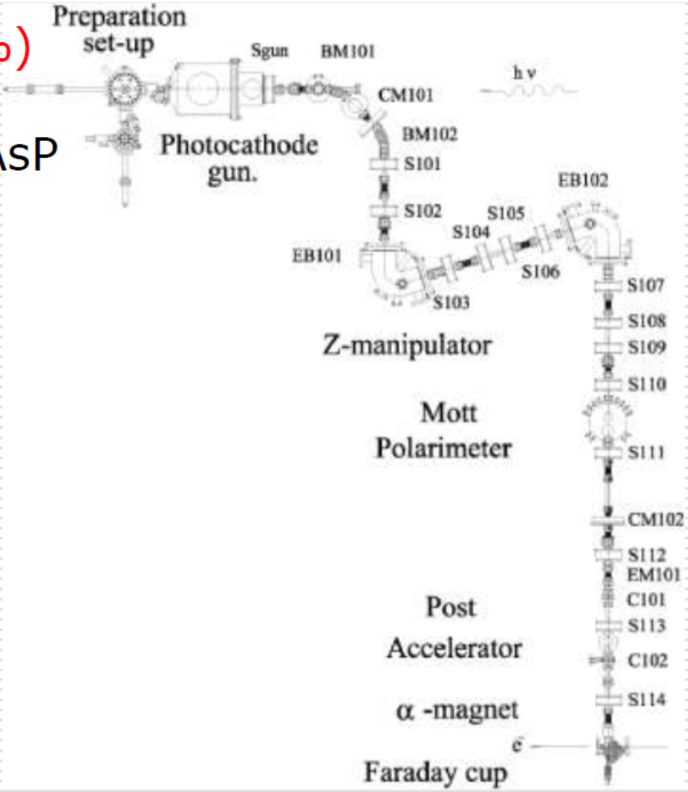
Electron polarization source

Beam polarization	60–80% (90%)
Cathode voltage	100 kV
Photocathode type	Strained InGaAsP
Laser type	Ti–Sapphire
Light wavelength	700–850 nm
Laser power in a pulse	200 W
Pulse duration	2.1 μs
Repetition rate	1 Hz (50 Hz)
Max. current from a gun	150 mA
Operational current	15–20 mA
Photocathode lifetime	190–560 hours



BINP e+ injector

Positron injector

Nominal Parameters

- Production: $N=2\cdot10^{10}$ e^+/sec
- Extraction Rate: 50 Hz

Upgrade

- New Electron Gun $N=2\cdot10^{10}$ $e^- \rightarrow 6\cdot10^{10}$ e^- (×3 times)
- New Optics for Positron Target (×1.5 times)
- Monochromatization of Positron Energy Spread (×2 times)
- Electron Beam Energy 300 MeV → 450 MэB (×1.5 times)
- Extraction Rate 50 Hz (w/o accumulate)
- 2 Bunches in Damping Ring

Total: $N = 2\cdot10^{11}$ e^+/sec

Parameters Tau-Charm (NSRL, China) (2017)

Table 1: Main Parameters for Accelerators, Phase 1

Design Goals	Value
Peak Luminosity	5×10^{34} cm^{-2}s^{-1}
Beam Energy	2GeV， 1-3.5GeV tunable
Current	1.5 A
Beam Emittance $\varepsilon_x/\varepsilon_y$	5/0.05 nm·rad
β_x^*/β_y^*	100/0.9 mm
Crossing Angle	60 mrad
Hourglass factor H	0.8
ξ_y	0.06
Circumstance	~600m

Table 2: Main Parameters for Accelerators, Phase 2

Design Goals	Value
Peak Luminosity	1×10^{35} cm^{-2}s^{-1}
Beam Energy	2GeV， 1-3.5GeV tunable
Current	2 A
Beam Emittance $\varepsilon_x/\varepsilon_y$	5/0.05 nm·rad
β_x^*/β_y^*	67/0.6 mm
Crossing Angle	60 mrad
Hourglass factor H	0.8
ξ_y	0.08
Circumstance	~600m

Tau-Charm Layout (Frascati) (Biagini)

Linac used for FEL science as well.

1. Linac tunnel
2. Modulator and klystron l
3. Damping Ring
4. Main Rings
5. Collider hall
6. Assembly hall
7. Vacuum Lab
8. Cryo Lab
9. Magnetic measurement
10. HVAC building
11. Electric station
12. Electric substation
13. Undulators tunnel
14. FEL building

Typical Tau-Charm Parameters (Frascati)

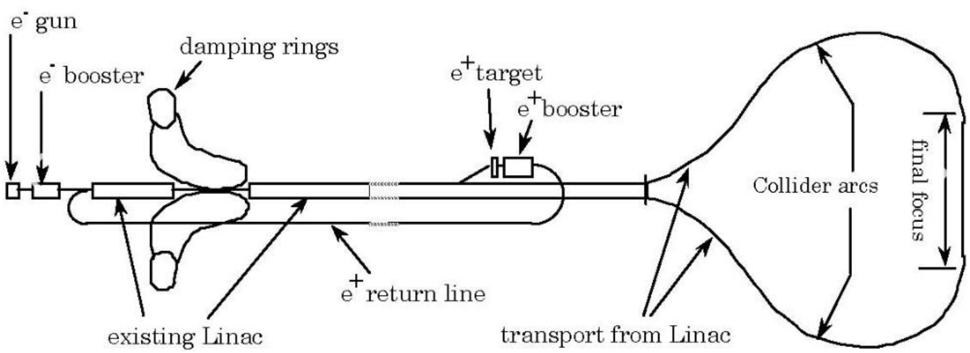
Table 1: Tau/Charm Main Parameters @ 2 GeV

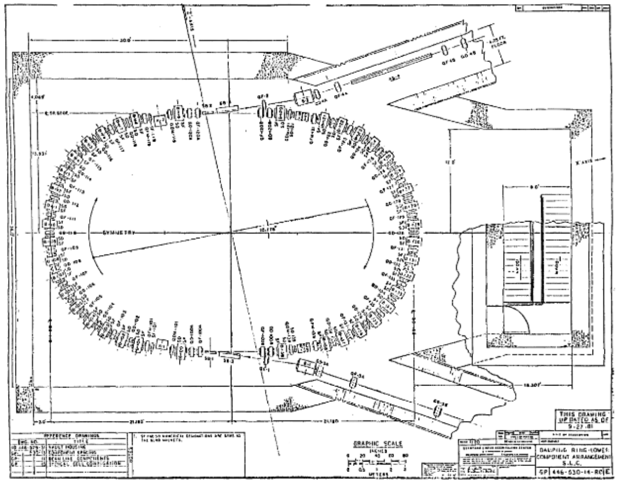
Parameter	Units	
Luminosity	cm^{-2} sec^{-1}	10^{35}
Beam energy	GeV	2
Circumference	m	341
X-angle (full)	mrad	60
Piwinski angle	rad	10.84
Beam-beam tune shift (x,y)		0.004,0.089
IP β (x,y)	cm	7, 0.06
IP σ (x,y)	μm	19, 0.09
Emittance x (Natural/IBS)	nm	2.85/5.13
Coupling factor	%	0.25
Bunch length (Natural/IBS)	mm	5/6.9
Damping times (x,y)	msec	35, 49
RF Frequency	MHz	476
Number of bunches		530
Num. particles/bunch		$2.34x10^{10}$
Beam current	A	1.75
Beam power	MW	0.16

Total N = $1.1x\ 10^{13}$

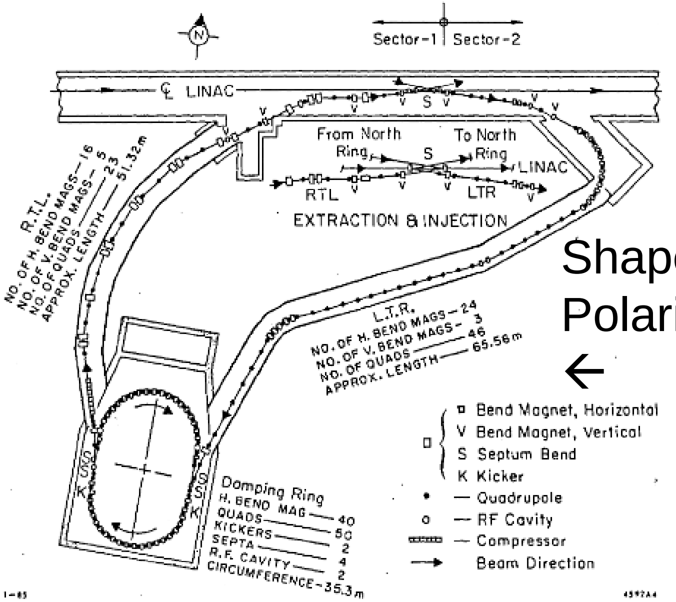
SLAC SLC Collider (120 Hz, 50GeV)

Damping ring has small width (~ 10 m)→





SLC Damping Ring (1.21 GeV), polarized e-, 35.3 m circ)



Shape for Polarization ←

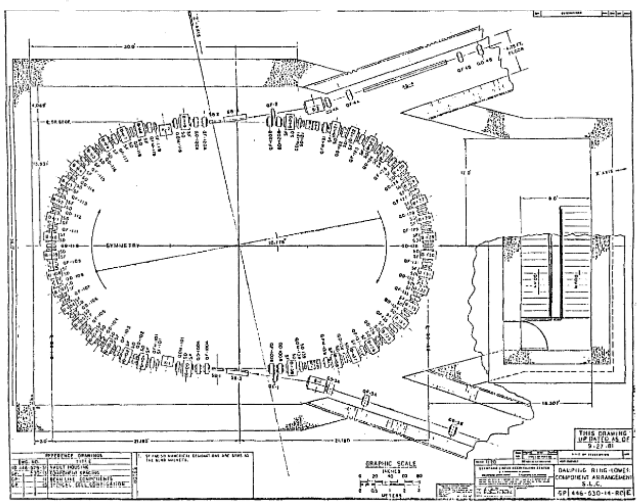


Table 6.1.1 General Design Parameters for the Damping Rings		
Energy	1.210	GeV
Circumference	35.270	m
Revolution Frequency	8.5	MHz
RF Frequency	714.000	MHz
Harmonic Number	84	
Transverse Damping Time	3.059	msec
Equilibrium Emittance		
(with full coupling)	9.1×10^{-9}	π rad m
Equilibrium rel. Energy spread	7.3×10^{-4}	
Momentum Comp. Factor	.01814	
Energy loss/Turn	93.1	keV
Bending Radius	2.0372	m
Bending Field	19.812	k gauss
CELL - Structure	1/2 FODO 1/2 F	
ν_x	~ 7.25	variable
ν_y	~ 3.25	variable
Acceptance		
in phase space	$\geq 4.13 \times 10^{-6}$	π rad m
in energy	$\geq \pm 1\%$	
RF System and Related Parameter		
RF - voltage	800	kV
phase	6.7°	
Synchrotron Frequency	107.3	kHz
tune	.0126	
Equilibrium Bunch length	5.9	mm
$\epsilon_c =$	1.9283	keV
I (2 bunches)	136.2	ma
P (synchrotron rad.)	12.68	kW

Injector Cost Estimation

An actual site for the injector usually has constraints:

Existing equipment: linac, damping rings , particle sources.

Geometrical constraints: Site boundaries, land elevation, buildings, shielding issues for neighbors

Personnel: technical expertise, cost of personnel, technical component costs

I will try to answer here with no external constriants:

What is the least expensive “green” field e+e- injector?

(Used here: California parametric cost estimates)

Parametric Cost Analysis for Various Injectors

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

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

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

For example, a linac accelerator costs more per meter than an accelerator transport line.

A linac tunnel cost more per meter than a transport line tunnel.

When an accelerator shares a tunnel with another accelerator, then only the incremental costs for the tunnel will be added.

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 much more complicated to calculate. Parametric cost estimate!

Injector Complex Components (costly)

- e+/e- LINAC
- e+ Target
- Damping ring
- Booster ring
- Polarization
- Spin Rotators

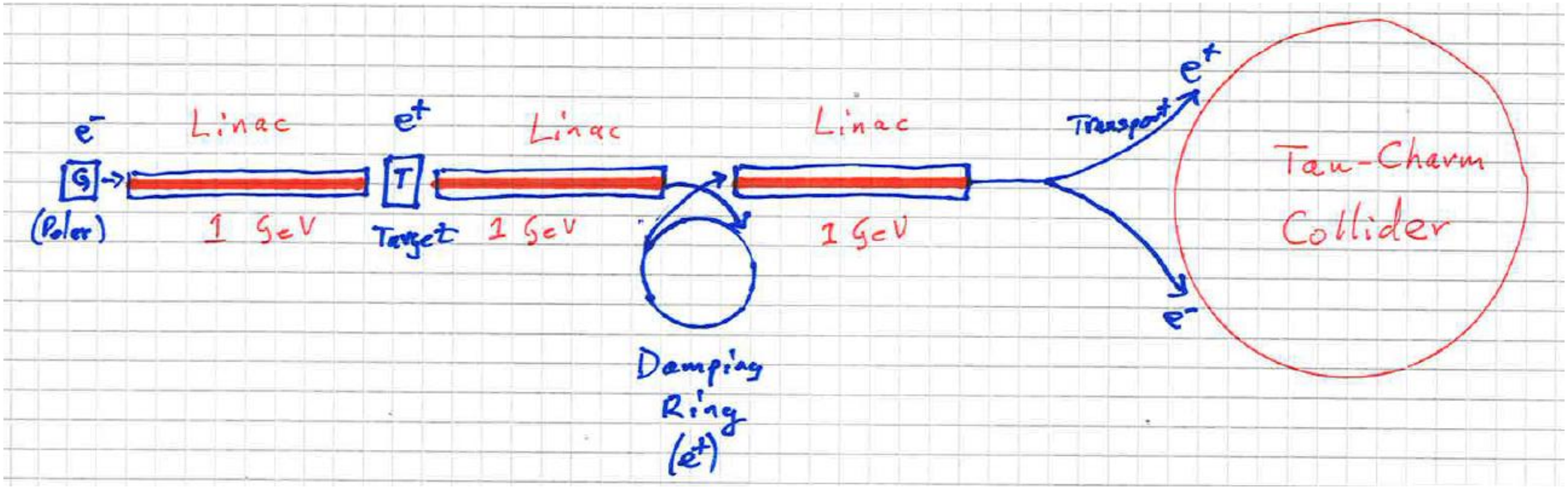
Injector Simple Components (inexpensive)

Transport tunnels

Transport lines

Ring injection lines

Tau-Charm Injector (Basic case) (Straight Linac)



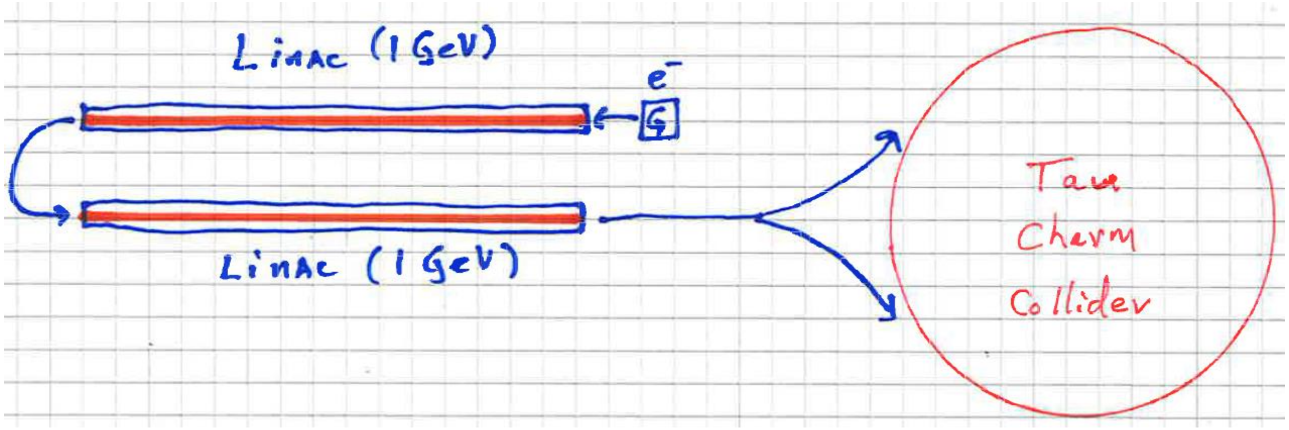
Parametric Costs for Straight Linac Case

Three Linac Case				
Component	Unit	Value	Parametric cost per unit	Total cost (Parametric)
Accel Linac	GeV	3	17	51
Accel Transport High E	m	60	0.15	9
Accel Transport Low E	m	10	0.05	0.5
Accel π Turn-around HE	m	2	8	16
Accel π Turn-around LE	m	0	4	0
Tunnel (linac)	m	180	0.2	36
Tunnel (Transport)	m	70	0.05	3.5
Tunnel (Damping Ring)	#	1	7	7
			Total =	123

More Compact Electron Injector (folded)

Two linacs share the housing and klystron gallery.

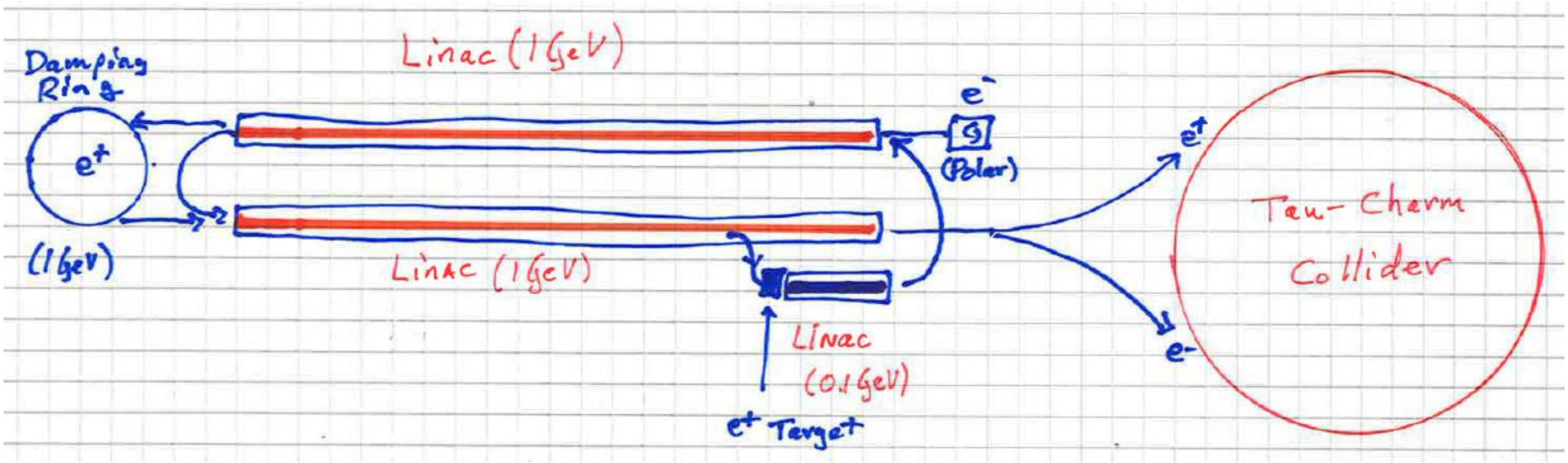
Half
SLC
Damping
Ring
→



Folded Full Tau-Charm Injector (e+ e-)

Positrons share many of the electron facilities.

Minimum cost would remove the positron linac on the right.



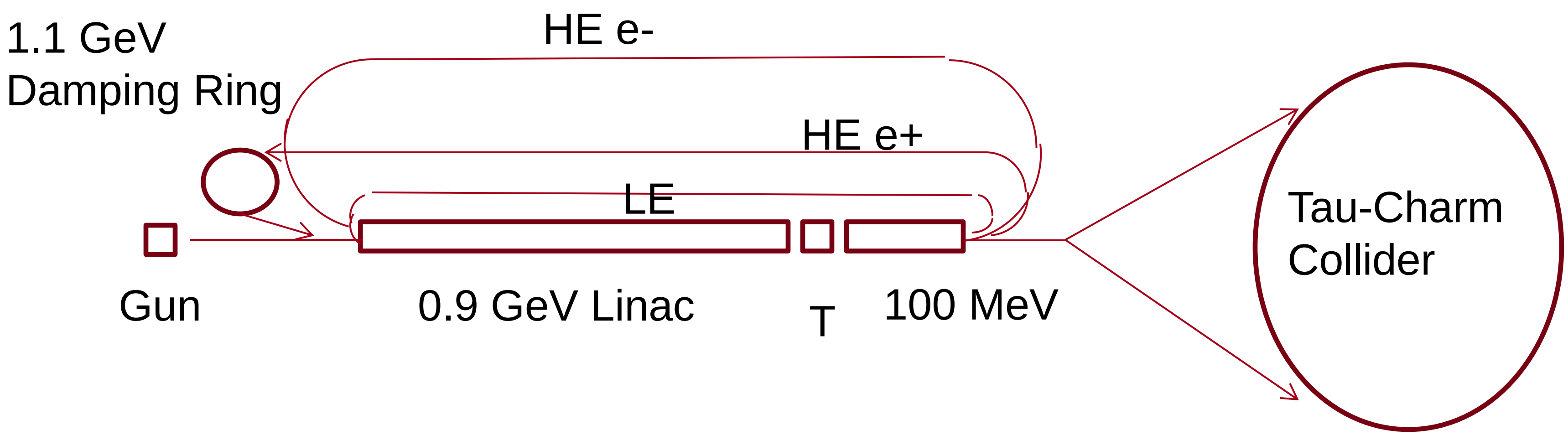
Folded Linac Injector Parametric Costs

SLAC

Folded Linac Case				
Component	Unit	Value	Parametric cost per unit	Total cost (Parametric)
Accel Linac	GeV	2	17	34
Accel Transport High E	m	60	0.15	9
Accel Transport Low E	m	10	0.05	0.5
Accel π Turn-around HE	#	3	8	24
Accel π Turn-around LE	#	1	4	4
Tunnel (linac)	m	60	0.2	12
Tunnel (Transport)	m	30	0.05	1.5
Tunnel (Damping Ring)	#	1	7	7
			Total =	92

Recirculating Linac Injector

For Tau-Charm collider, the injection energy is low enough that a wrap-around recirculation time is with in one linac pulse (~3 micro-second).

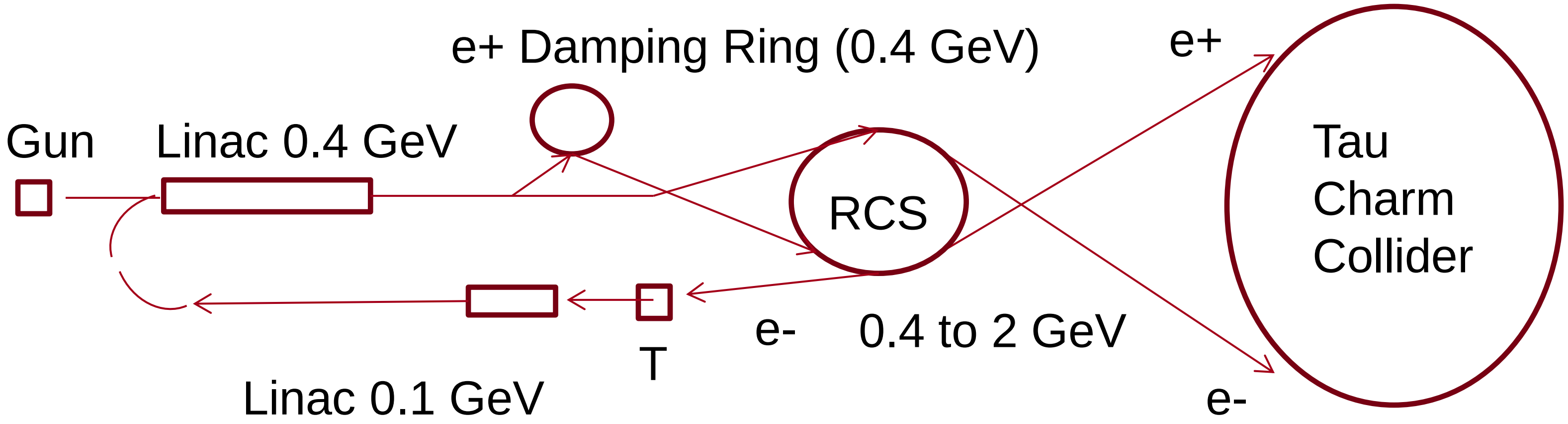


Recirculating Linac Parametric Costs

SLAC

Recirculating Linac Case				
Component	Unit	Value	Parametric cost per unit	Total cost (Parametric)
Accel Linac	GeV	1	17	17
Accel Transport High E	m	140	0.15	21
Accel Transport Low E	m	70	0.05	3.5
Accel π Turn-around HE	#	4	8	32
Accel π Turn-around LE	#	2	4	8
Tunnel (linac)	m	60	0.2	12
Tunnel (Transport)	m	20	0.05	1
Tunnel (Damping Ring)	#	0	7	0
			Total =	95

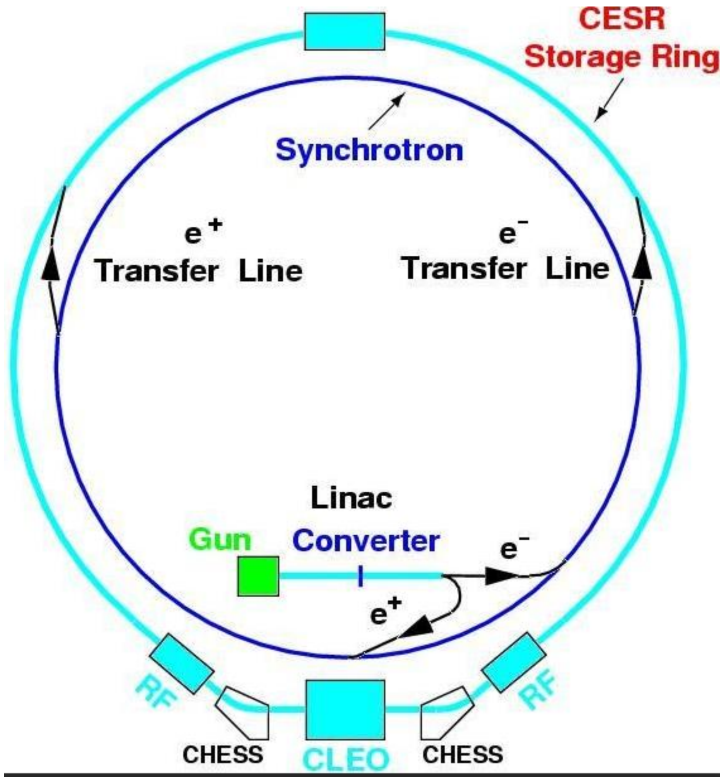
Rapid Cycling Synchrotron (RCS)+Low Energy Linac Injector



Cornell Rapid Synchrotron (12 GeV, 60Hz, 768 m)

CESR

Synchrotron injector



NSLS-II Injector Synchrotron (0.2 → 3 GeV, 158 m)

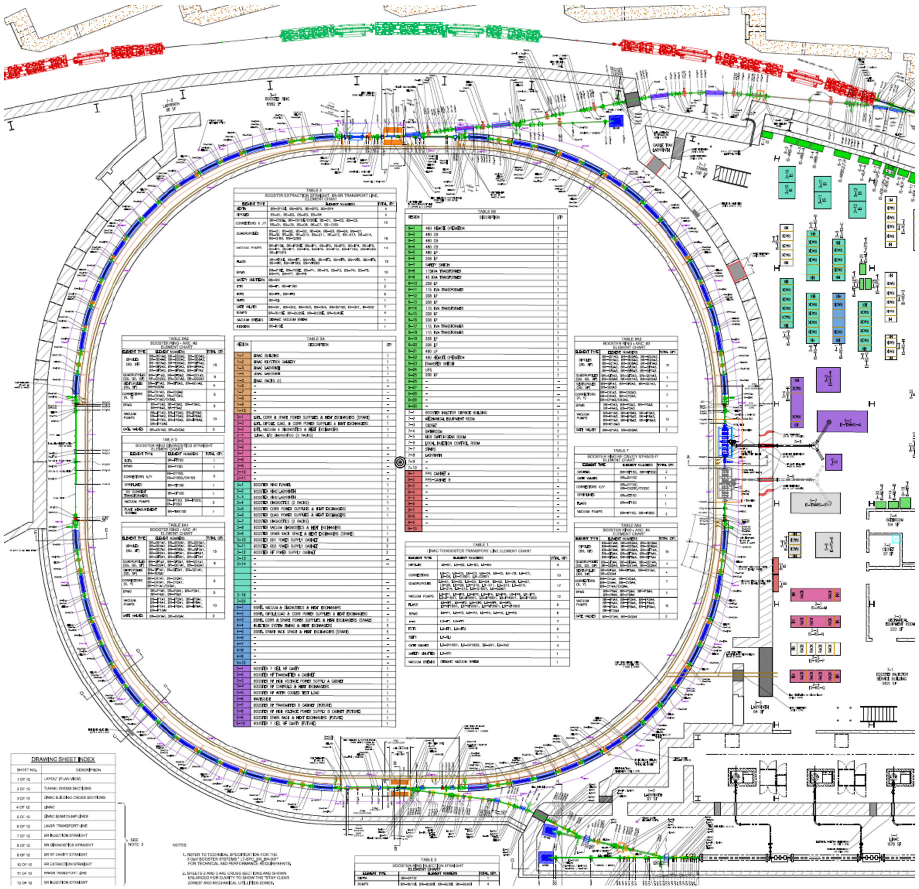


Table 1: Booster ring's parameters

Parameter	Value
Emittance, nm	39
Circumference, m	158.4
Booster current, mA	20
RF frequency, MHz	499.68
RF voltage, MV	1.2
Harmonic number	264
X/Y tune	9.64/3.41
X/Y chromaticity	-9.9/-12.9
Momentum Compaction	0.0084
Energy loss per turn, keV	686
X/Y/E damping time, ms	4.8/4.7/2.3
Damped energy spread, %	0.82
Damped bunch length, mm	16.2

RSC+Linac Parametric Costs

RCS + Small Linac Case				
			Parametric	Total cost
Component	Unit	Value	cost per unit	(Parametric)
Accel Linac	GeV	0.5	17	8.5
Accel Transport High E	m	60	0.15	9
Accel Transport Low E	m	60	0.05	3
Accel π Turn-around HE	#	4	8	32
Accel π Turn-around LE	#	3	4	12
Tunnel (linac)	m	30	0.2	6
Tunnel (Transport)	m	20	0.05	1
Tunnel (Damping Ring)	#	3	7	21
			Total =	93

Cost summary: Tau-Charm Injector Types Compared (Parametric Costs)

Common components that need to be added to all injectors (same for all):

- Gun e- source
- Injection transport lines into rings
- Positron target and e+ capture section.

Cost Summary:	Relative cost
Straight linac injector	1.0
Folded linac injector	0.76
Recirculating linac injector	0.77
Rapid cycling synchrotron + low energy linac injector	0.75

Conclusion

The solid e+ and e- injector is important for a Tau-Charm Collider due to short beam lifetimes and the need for polarized electrons.

Positron production adds complications.

Polarization adds complications.

Site constraints often dictates the design of the injector.

Parametric cost analysis indicates that a “green field” folded linac, a recirculating linac, or a RCS are the least expensive injectors for a tau-charm factory. Exact cheapest depends on local conditions.