Energy Efficiency
in
Circular Particle Accelerators

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SLAC
FCC Meeting in Rome
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U.S. DEPARTMENT OF ENERGY
Office of Science

SLAC NATIONAL ACCELERATOR LABORATORY

Abstract

The power and related energy usage of recent and future circular accelerators is becoming an ever increasing issue as the circumference and beam currents of these accelerators grow with each new generation. The demands and efficiencies of the various energy source terms in circular colliders will be covered. Power reduction possibilities will be evaluated looking several new ideas. Directions of future power studies will be discussed.

Thank you

Inputs from:

F. Zimmermann

Q. Qin

W. Chou

M. Sullivan

R. Erickson

K. Oide

A. Novokhatski

M. Biagini

M. Kemp

E. Jensen

T. Kageyama

Accelerator Efficiency Topics

Review recent actual or designed high current accelerators:

- PEP-II (SLAC)
- SuperB (Frascati) (Design)
- KEKB → SuperKEKB (KEK)
- LEP (CERN)
- LHC (CERN)

New Proposals

- CEPC (IHEP) (Design)
- FCC-ee (CERN) (Design)
- FCC-hh (CERN) (Design)

On going developments on accelerator efficiency:

- Beam physics (energy, HOMs, emittances)
- High Q cavities
- Depressed collector klystrons
- Solid-State Amplifiers (SSA)

PEP-II klystron

PEP-II B-Factory (9 x 3 GeV)
RF Klystrons → (1.2 MW RF) (2 MW AC line)

HER = 10 klystrons, LER = 5 klystrons

SLAC campus = 15 MW

Linac running at 30 Hz = 8 MW

PEP-II magnets = 6 MW

PEP-II RF = (9 x 3.1 GeV)
(2.8 A x 1.8 A) = 29 MW

Utilities = 7MW

Total (wall) = 50 MW

PEP-II RF Parameters (~2006) (McIntosh)

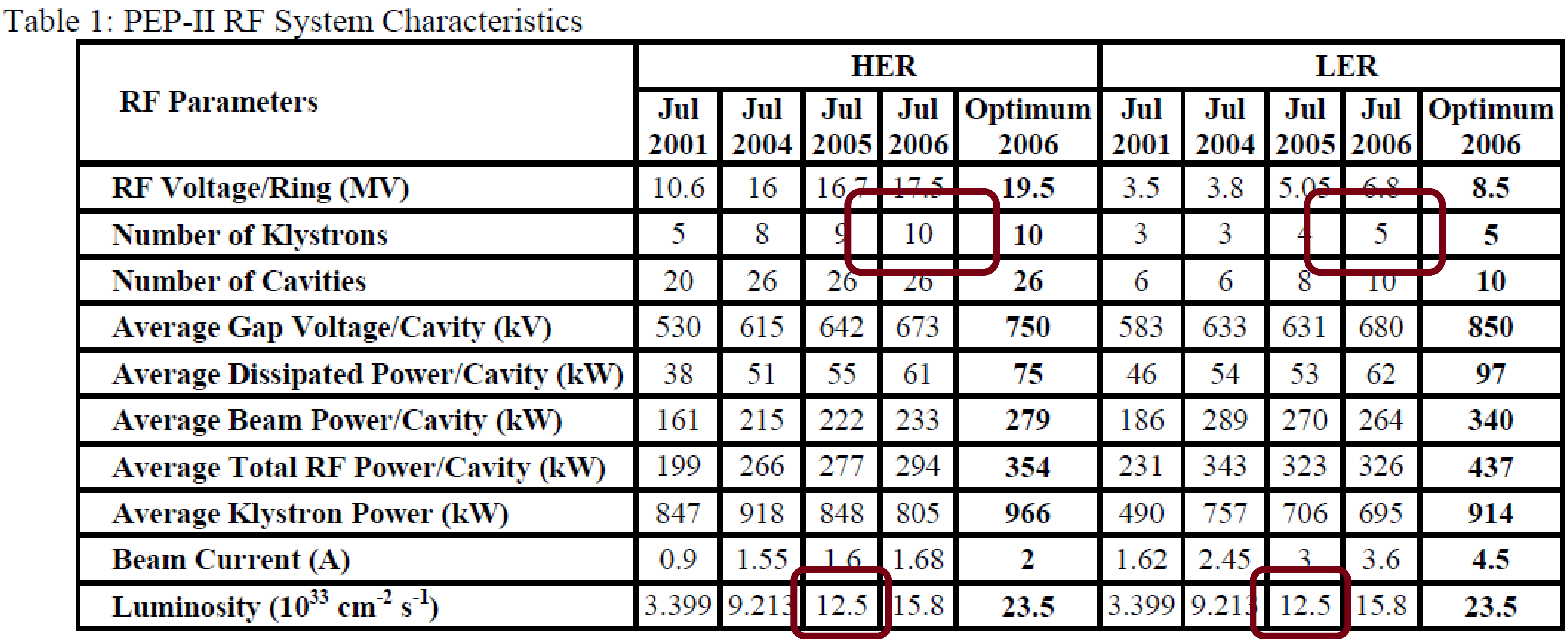


Table 1: PEP-II RF System Characteristics

RF Parameters	HER					LER				
	Jul 2001	Jul 2004	Jul 2005	Jul 2006	Optimum 2006	Jul 2001	Jul 2004	Jul 2005	Jul 2006	Optimum 2006
RF Voltage/Ring (MV)	10.6	16	16.7	17.5	**19.5**	3.5	3.8	5.05	6.8	**8.5**
Number of Klystrons	5	8	9	10	**10**	3	3	4	5	**5**
Number of Cavities	20	26	26	26	**26**	6	6	8	10	**10**
Average Gap Voltage/Cavity (kV)	530	615	642	673	**750**	583	633	631	680	**850**
Average Dissipated Power/Cavity (kW)	38	51	55	61	**75**	46	54	53	62	**97**
Average Beam Power/Cavity (kW)	161	215	222	233	**279**	186	289	270	264	**340**
Average Total RF Power/Cavity (kW)	199	266	277	294	**354**	231	343	323	326	**437**
Average Klystron Power (kW)	847	918	848	805	**966**	490	757	706	695	**914**
Beam Current (A)	0.9	1.55	1.6	1.68	**2**	1.62	2.45	3	3.6	**4.5**
Luminosity (10^{33} cm^{-2} s^{-1})	3.399	9.213	12.5	15.8	**23.5**	3.399	9.213	12.5	15.8	**23.5**

July 2006 luminosity projections were unrealized.

Approximate Design SuperB Factory Site Power (3 km ring)

Campus +detector = 5 MW

Linac and e+ at 30 Hz = 10 MW

Magnets (~1.5 x PEP-II) = 10 MW

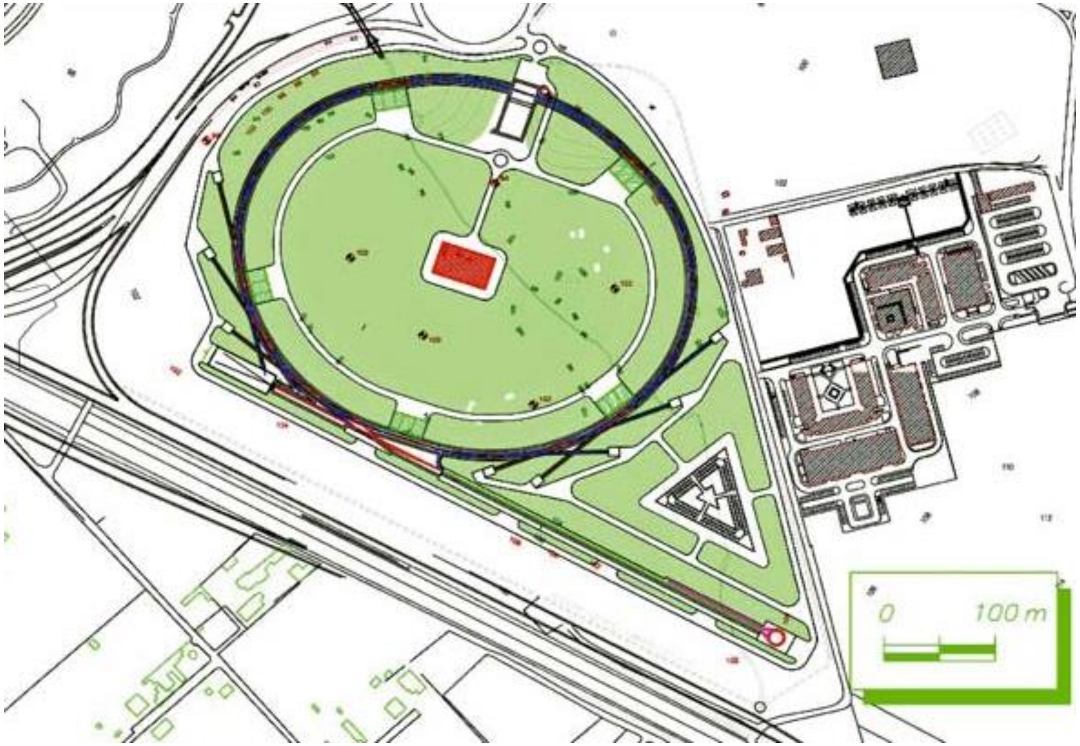
RF (4 x 7 GeV) (2.5 A x 1.4 A) = 22.4 x 2=45 MW

Cooling = 5 MW

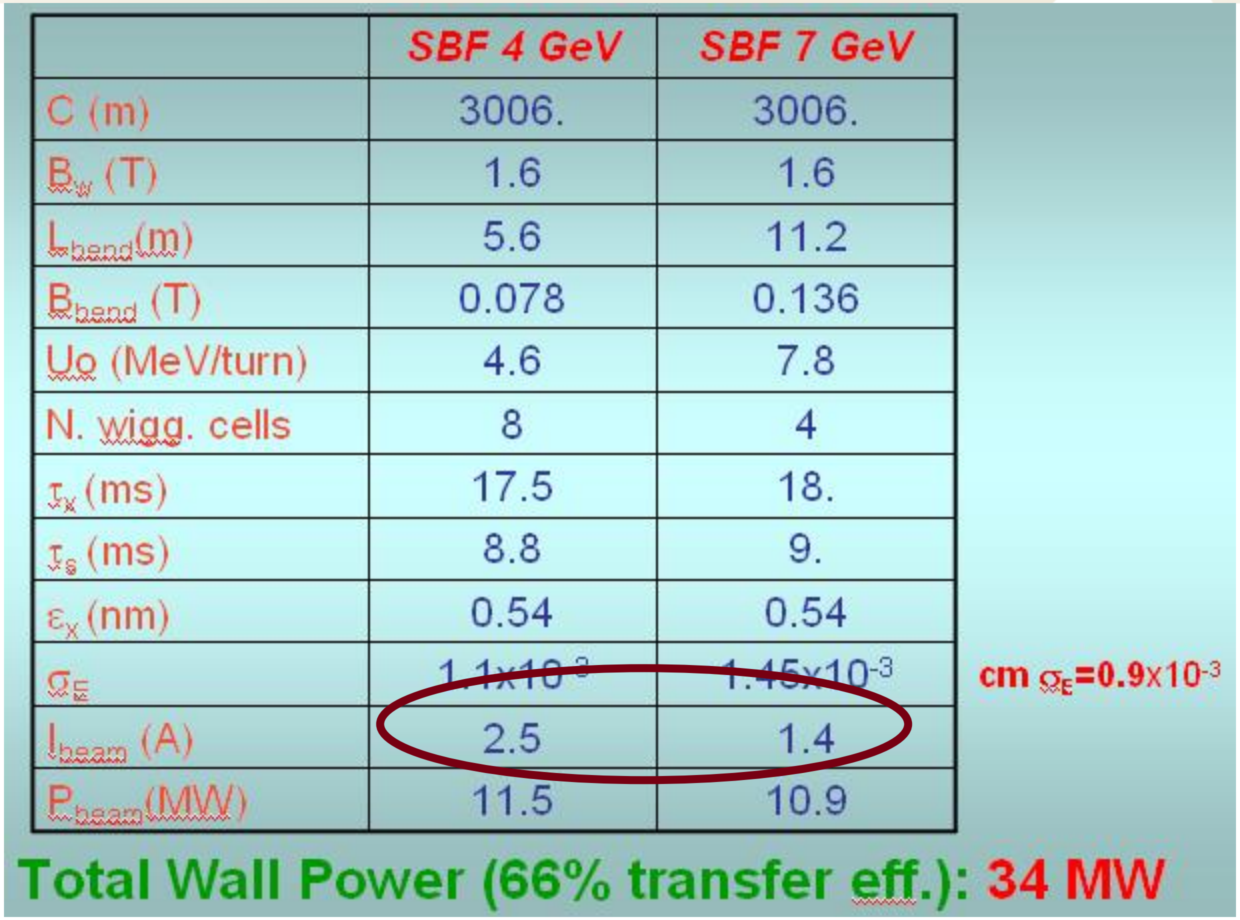
Total = ~75 MW

Frascati

RF AC efficiency = 50% =(65% klystron+90% power supply + 15% off klystron peak for beam stability feedback)



SuperB proposed at Frascati (M. Biagini April 2006)



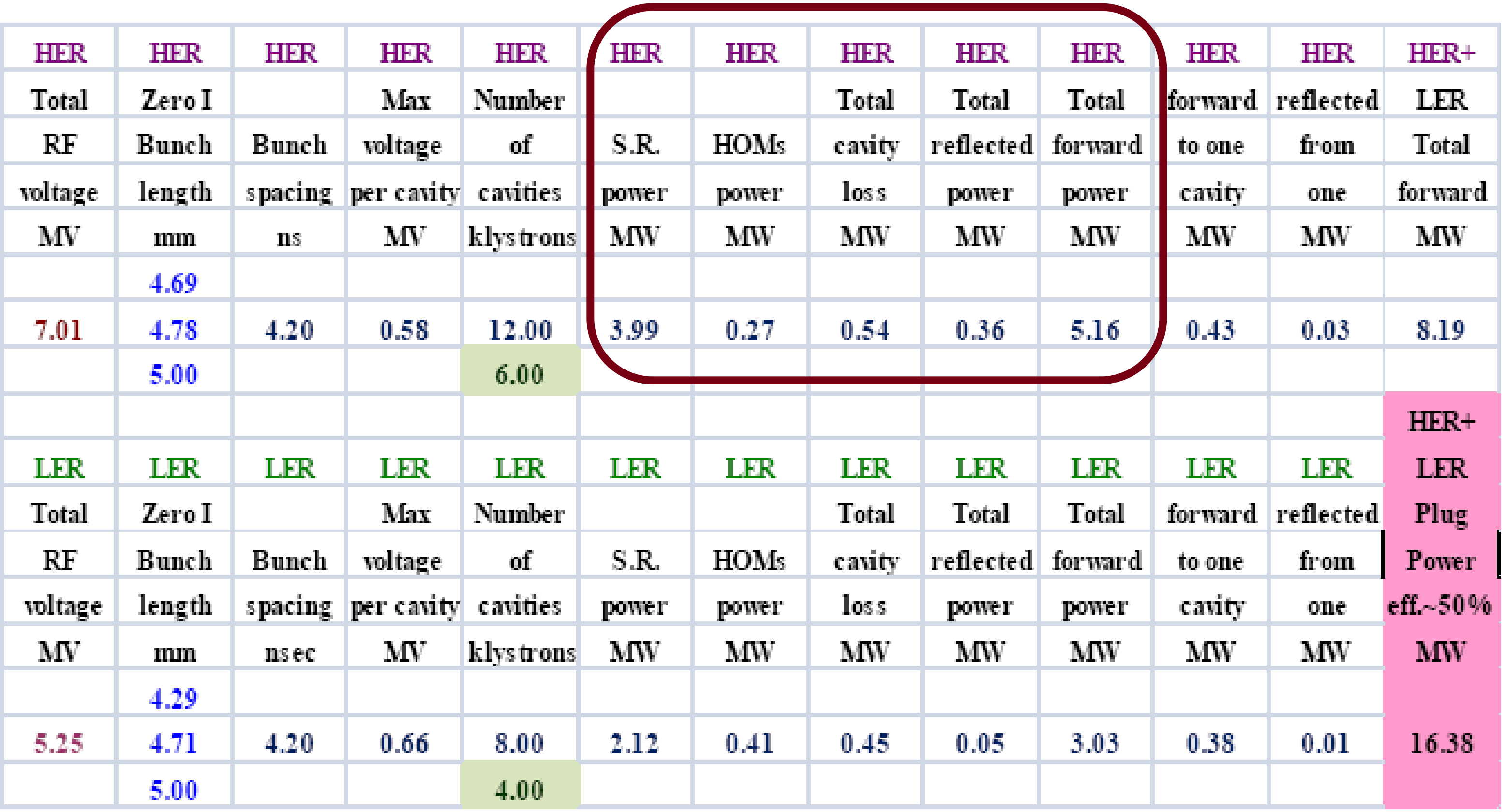
	SBF 4 GeV	SBF 7 GeV
C (m)	3006.	3006.
B_w (T)	1.6	1.6
L_{bend}(m)	5.6	11.2
B_{bend} (T)	0.078	0.136
Uo (MeV/turn)	4.6	7.8
N. wigg. cells	8	4
τ_x (ms)	17.5	18.
τ_s (ms)	8.8	9.
ε_x (nm)	0.54	0.54
σ_E	$1.1\text{x}10^{-3}$	$1.45\text{x}10^{-3}$
I_{beam} (A)	2.5	1.4
P_{beam}(MW)	11.5	10.9

cm σ_E=0.9x10^{-3}

Total Wall Power (66% transfer eff.): 34 MW

AC efficiency is about 50% =(65% klystron+90% power supply + 15% off klystron peak for beam stability feedback)

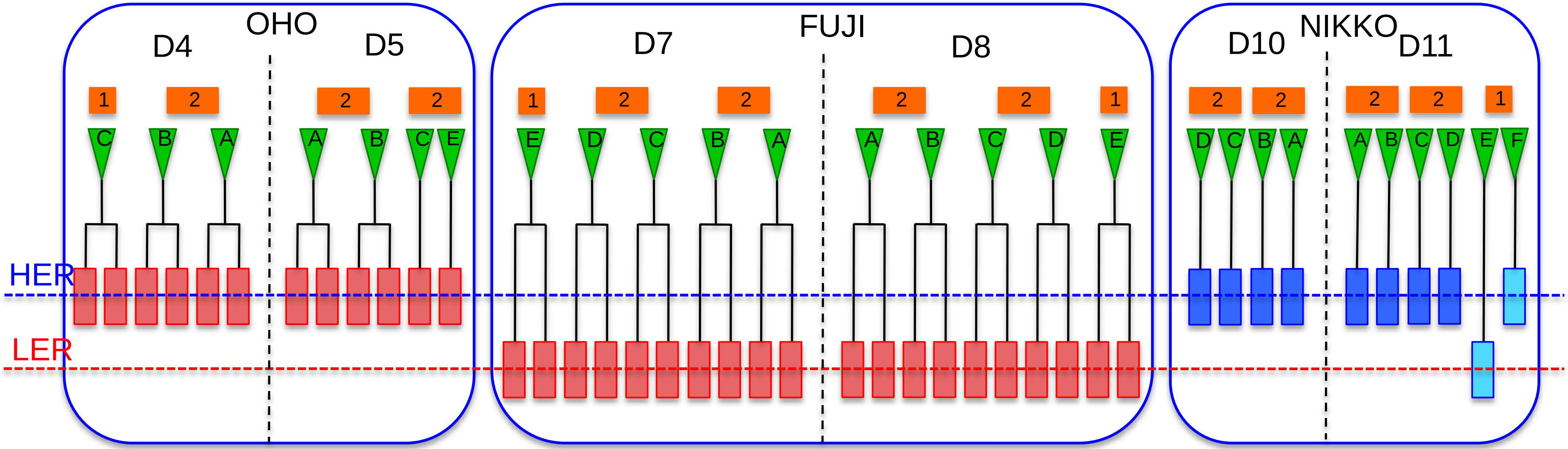
SuperB RF Parameters (A. Novokhatski)



HER Total RF voltage MV	HER Zero I Bunch length mm	HER Bunch spacing ns	HER Max voltage per cavity MV	HER Number of cavities klystrons	HER S.R. power MW	HER HOMs power MW	HER Total cavity loss MW	HER Total reflected power MW	HER Total forward power MW	HER forward to one cavity MW	HER reflected from one MW	HER+ LER Total forward MW
	4.69											
7.01	4.78	4.20	0.58	12.00	3.99	0.27	0.54	0.36	5.16	0.43	0.03	8.19
	5.00			6.00								

LER Total RF voltage MV	LER Zero I Bunch length mm	LER Bunch spacing nsec	LER Max voltage per cavity MV	LER Number of cavities klystrons	LER S.R. power MW	LER HOMs power MW	LER Total cavity loss MW	LER Total reflected power MW	LER Total forward power MW	LER forward to one cavity MW	LER reflected from one MW	HER+ LER Plug Power eff.~50% MW
	4.29											
5.25	4.71	4.20	0.66	8.00	2.12	0.41	0.45	0.05	3.03	0.38	0.01	16.38
	5.00			4.00								

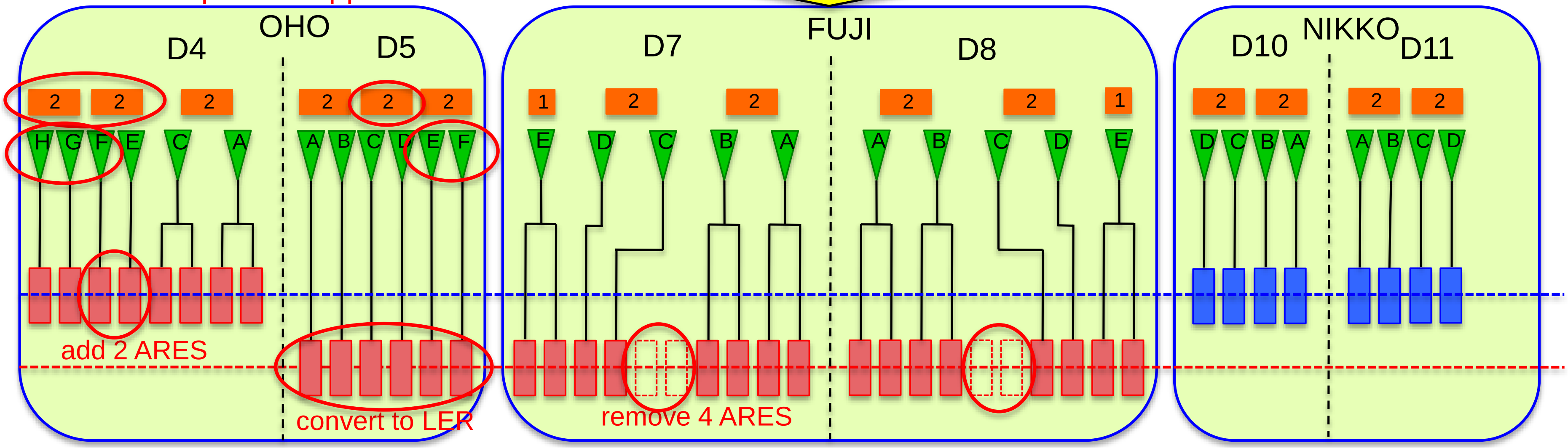
KEKB-RF



SuperKEKB-RF (phase 1)

add 5 klystrons, HP&LL
add 3 power supplies

27 → 30 klystrons



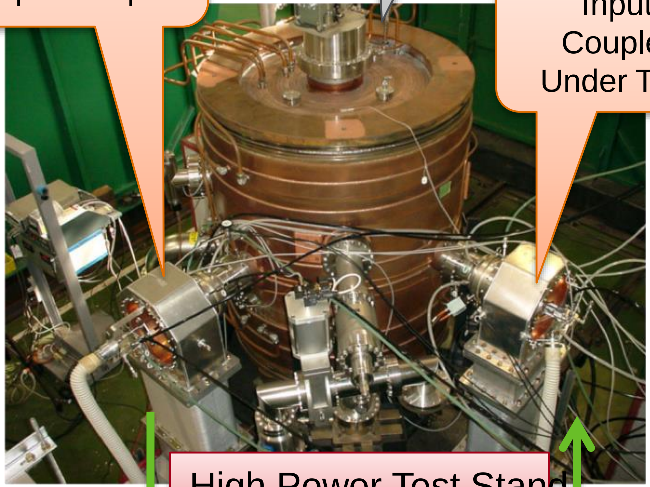
add 2 ARES

convert to LER

remove 4 ARES

- ▼ Klystron, HP&LLRF system
- 2 Type “A” power supply (for two klystrons)
- 1 Type “B” power supply (for one klystron)
- 🟥 ARES cavity
- 🟦 SC cavity
- ▯ SC crab

SuperKEKB ARES and SC RF Cavity Systems



ARES Storage Cavity

Input Coupler used as Output Coupler

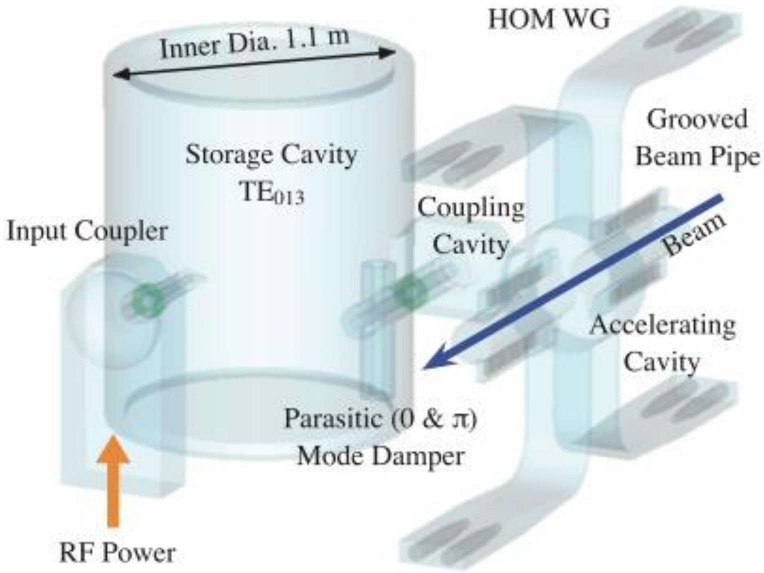
Input Coupler Under Test

High Power Test Stand

To 1MW Water Load

RF Power from 1MW CW Klystron (TOSHIBA E3786)

T. Kageyama et al.

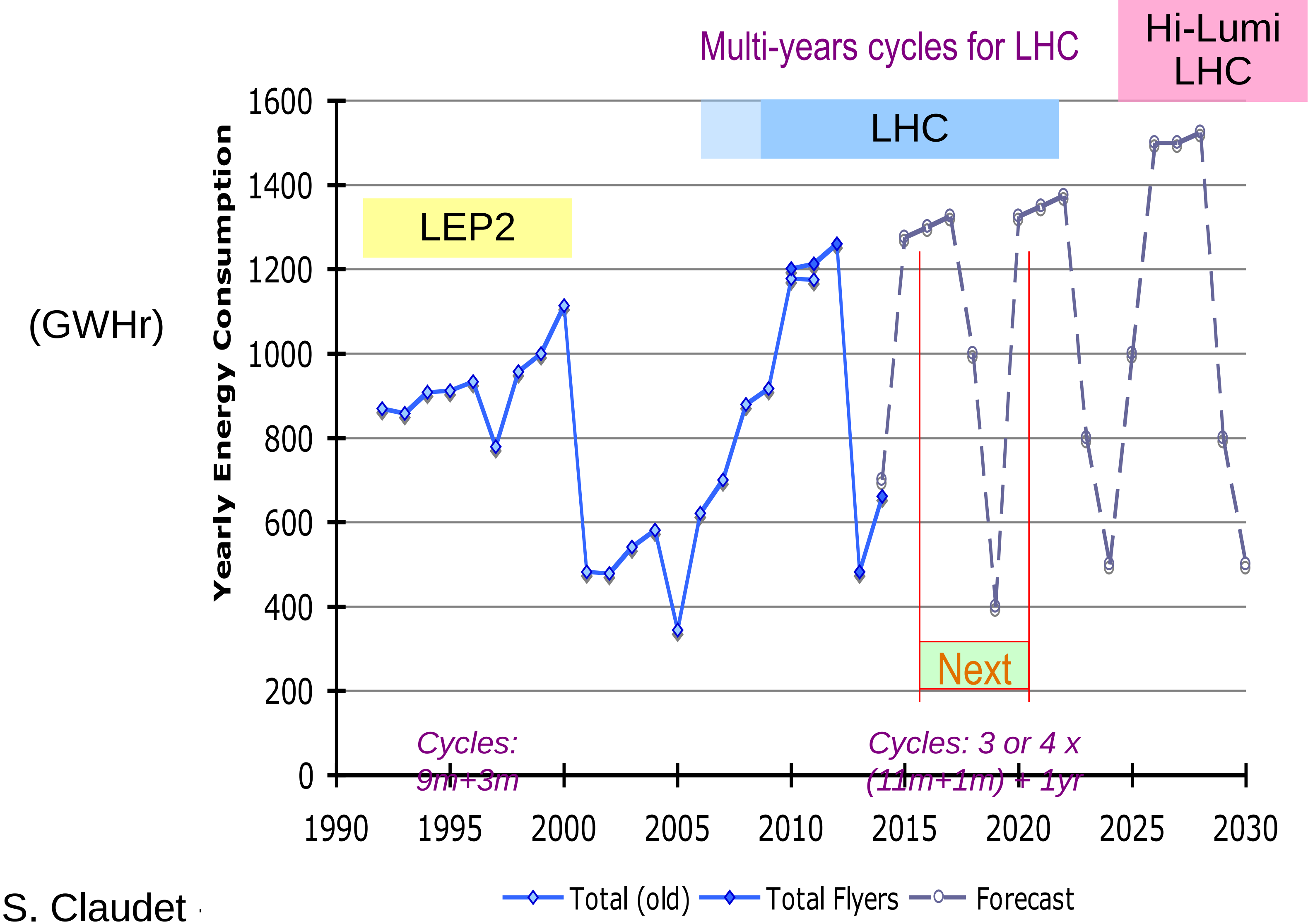


KEKB and SuperKEKB Beam Parameters

		KEKB		Nano-beam	
		LER	HER	LER	HER
Energy	GeV	3.5	8	4	7
Beam current	A	1.8	1.4	3.60	2.62
Bunch length	mm	6~7	6~7	6	5
No. bunches		1584		2503	
Energy loss/turn	MV	1.64	3.48	2.15	2.50
Radiation Loss	MW	2.95	4.87	7.74	6.55
Loss factor, assumed	V/pC	-	-	35	40
Parasitic Loss	MW	-	-	1.82	1.10
Total Beam Power	MW	~ 3.5	~ 5.0	9.56	7.65
RF Voltage	MV	8.0	13~15	8.4	6.7

RF beam pwr
= 17 MW
→ 35 MW wall

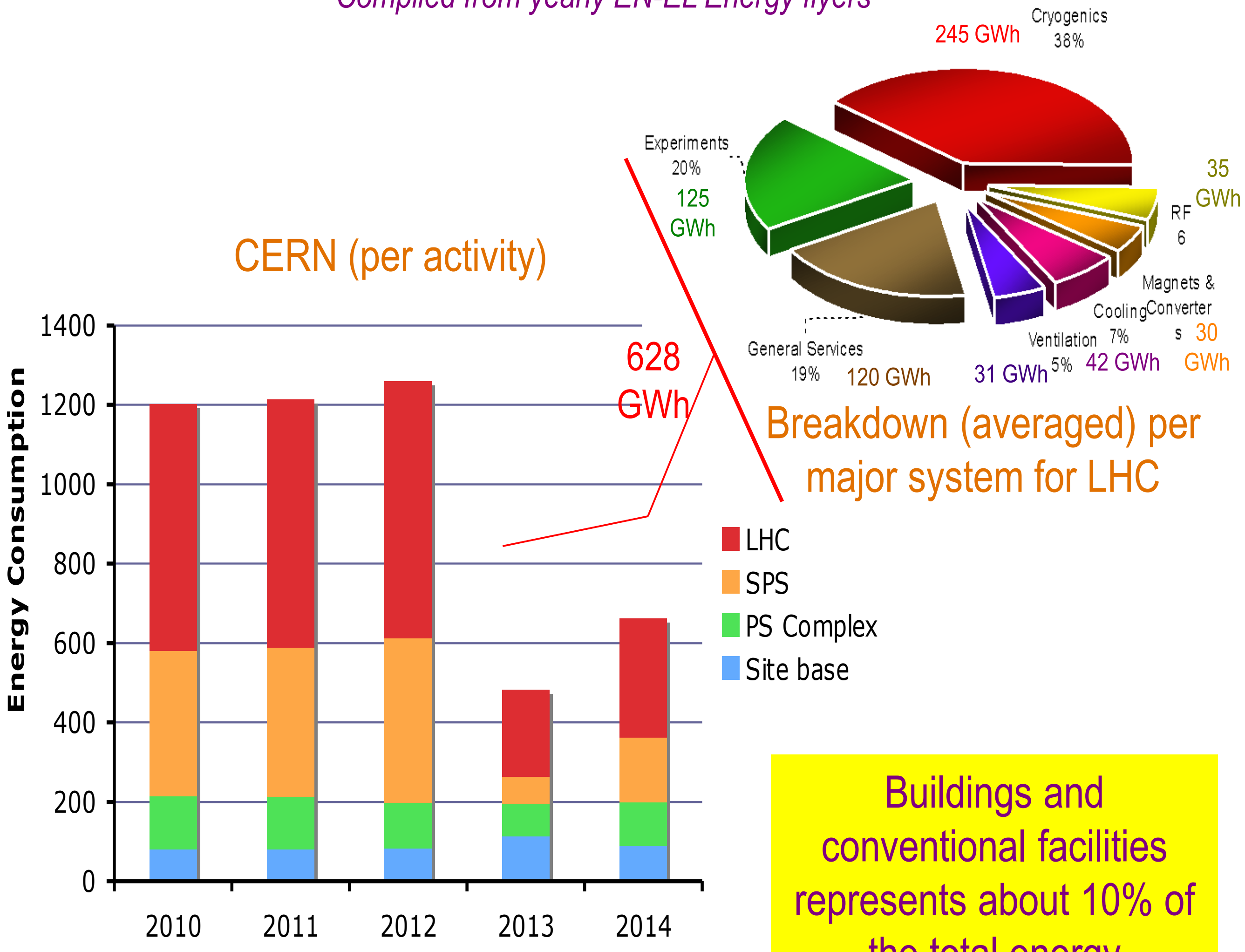
CERN Energy Consumption (Zimmermann…)



S. Claudet - CERN Procurement Strategy

CERN recent energy consumption

Compiled from yearly EN-EL Energy flyers



CERN (per activity)

Breakdown (averaged) per major system for LHC

Typical cycle of 3-4 years up, then 1-2 year down

Buildings and conventional facilities represents about 10% of the total energy consumption

CEPC (IHEP) Power from Pre-CDR (2015)

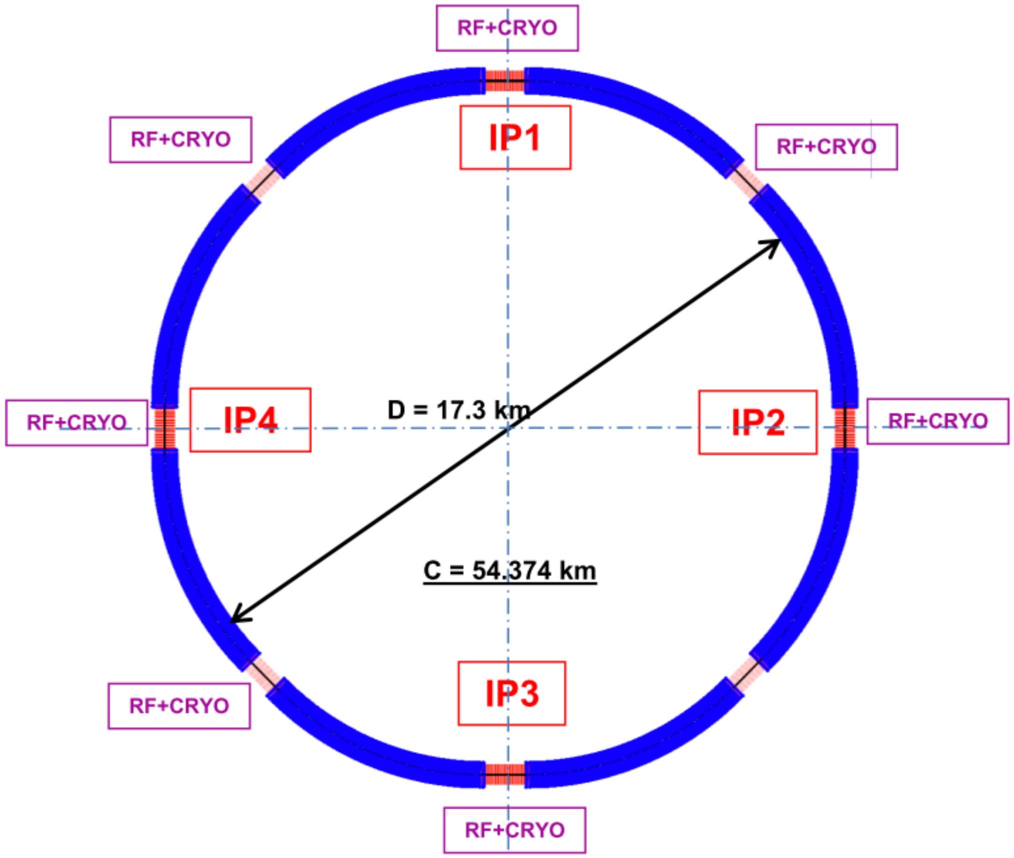
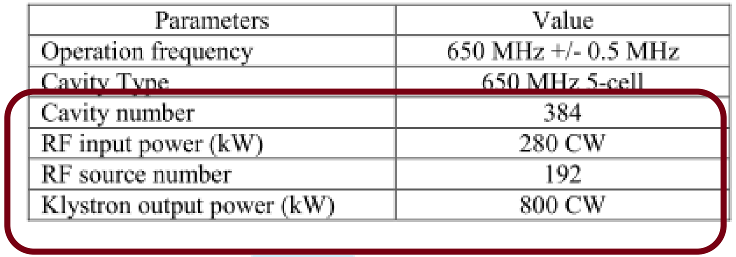


Table 5.2.2: CEPC collider SRF system parameters



Parameters	Value
Operation frequency	650 MHz +/- 0.5 MHz
Cavity Type	650 MHz 5-cell
Cavity number	384
RF input power (kW)	280 CW
RF source number	192
Klystron output power (kW)	800 CW

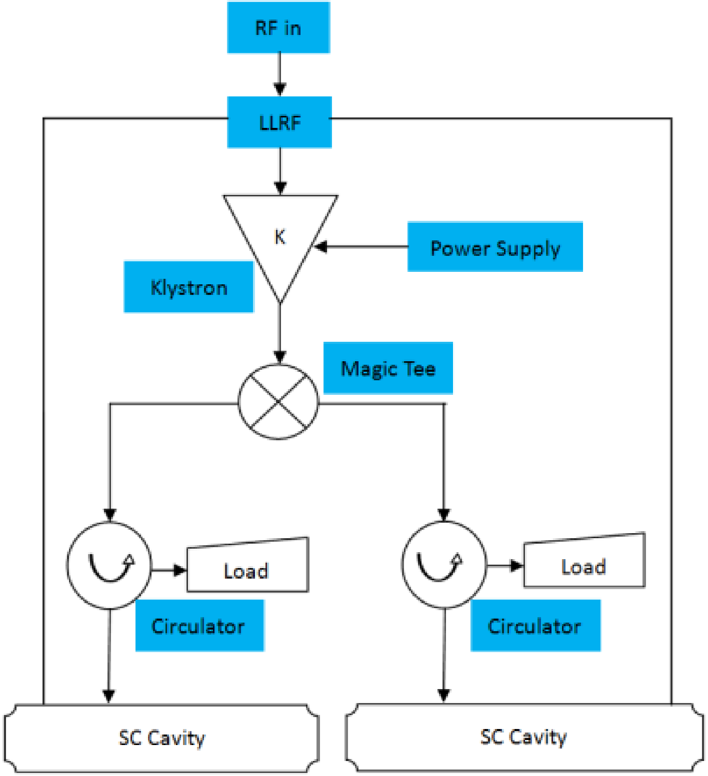


Figure 5.2.1: RF power source configuration

CEPC Linac RF Power Source

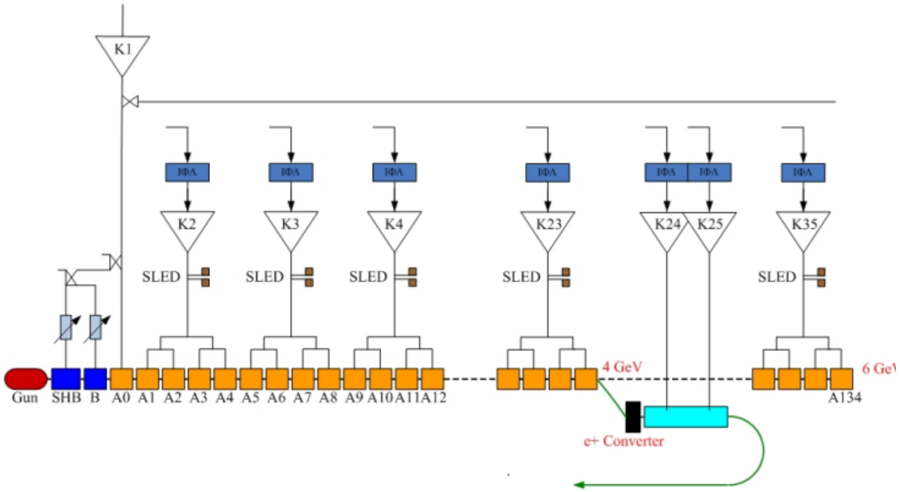


Figure 5.2.3: Simplified schematic of the Linac RF power source

Table 5.2.7: Parameters of 80 MW klystron

Parameters	Value
Frequency (MHz)	2856
Output power (MW)	80
Efficiency (%)	42
Gain (dB)	53
Pulse length (us)	4
Pulse rate (pps)	100
Beam voltage (kV)	400
Beam current (A)	488
Drive power (W)	350

Table 5.2.8: Main specifications of the modulator

Parameters	Value
Peak output power (MW)	200
Average output power (kW)	80
PFN charging voltage (kV)	50
PFN impedance (Ω)	2.85
Pulse width (us)	>4 μs (flat top)
Pulse flatness (%)	±0.15
Pulse rate (pps)	100
Pulse transformer turns ratio	1:17

CEPC Injector ring power (solid state amplifiers SSA)

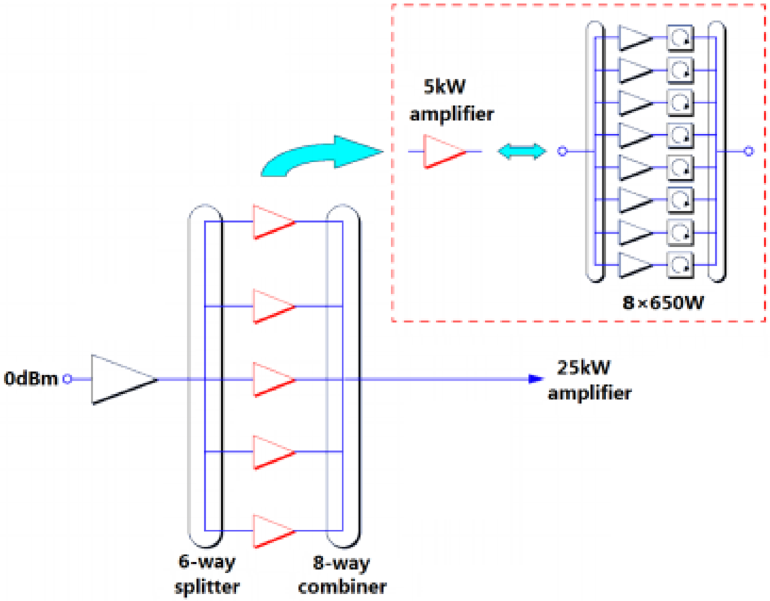
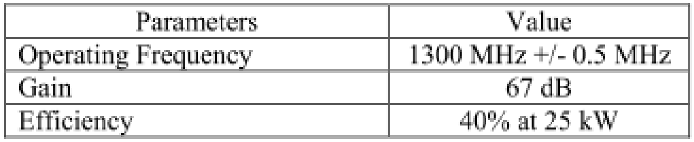


Figure 5.2.2: 25 kW amplifier basic topology

The output of the each module drives a common WR650 waveguide into superconducting cavity. The amplifier specifications are listed in Table 5.2.6.

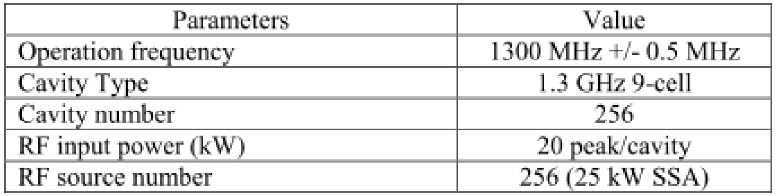
Table 5.2.6: Specifications of the Amplifier



Parameters	Value
Operating Frequency	1300 MHz +/- 0.5 MHz
Gain	67 dB
Efficiency	40% at 25 kW

Work in industry ongoing to improve SSA efficiency

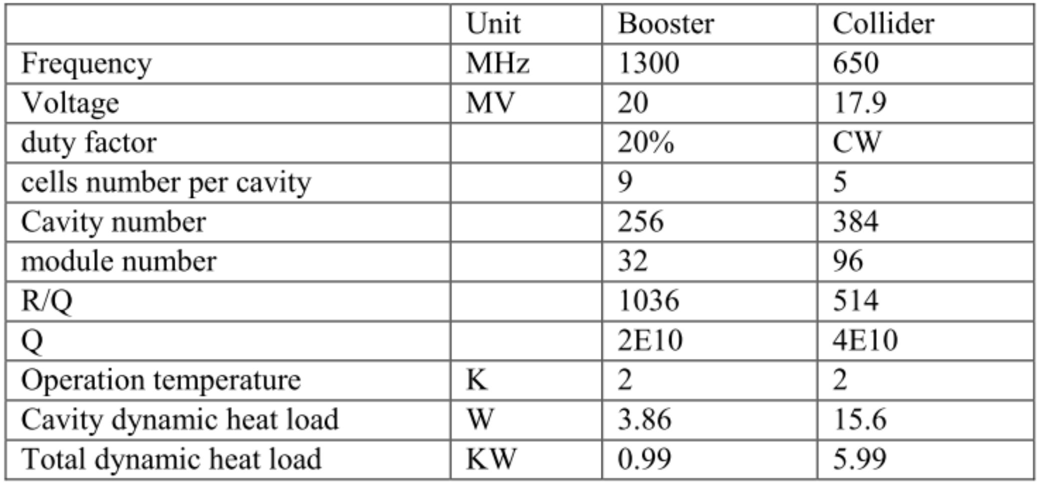
Table 5.2.5: CEPC Booster SRF system parameters



Parameters	Value
Operation frequency	1300 MHz +/- 0.5 MHz
Cavity Type	1.3 GHz 9-cell
Cavity number	256
RF input power (kW)	20 peak/cavity
RF source number	256 (25 kW SSA)

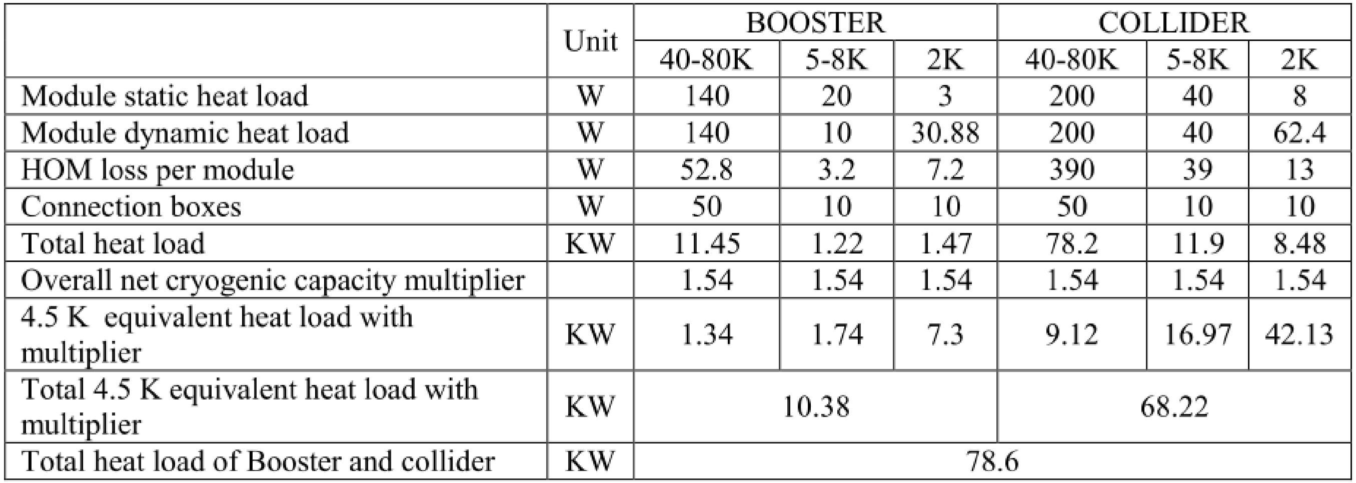
CEPC Cryogenic Heat Load

Table 5.3.1: Parameters of the Booster and collider ring cavities



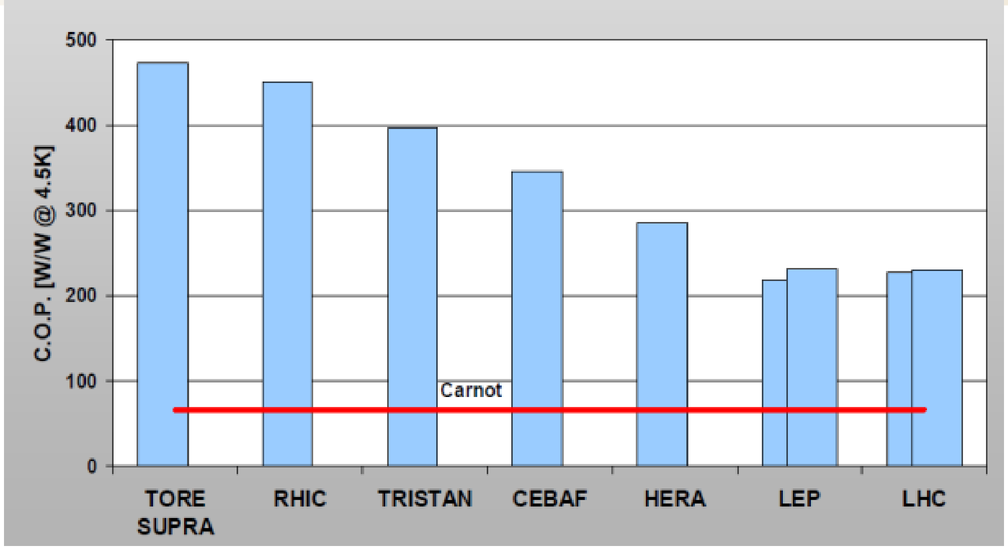
	Unit	Booster	Collider
Frequency	MHz	1300	650
Voltage	MV	20	17.9
duty factor		20%	CW
cells number per cavity		9	5
Cavity number		256	384
module number		32	96
R/Q		1036	514
Q		2E10	4E10
Operation temperature	K	2	2
Cavity dynamic heat load	W	3.86	15.6
Total dynamic heat load	KW	0.99	5.99

Table 5.3.2: CEPC heat load



	Unit	BOOSTER			COLLIDER		
		40-80K	5-8K	2K	40-80K	5-8K	2K
Module static heat load	W	140	20	3	200	40	8
Module dynamic heat load	W	140	10	30.88	200	40	62.4
HOM loss per module	W	52.8	3.2	7.2	390	39	13
Connection boxes	W	50	10	10	50	10	10
Total heat load	KW	11.45	1.22	1.47	78.2	11.9	8.48
Overall net cryogenic capacity multiplier		1.54	1.54	1.54	1.54	1.54	1.54
4.5 K equivalent heat load with multiplier	KW	1.34	1.74	7.3	9.12	16.97	42.13
Total 4.5 K equivalent heat load with multiplier	KW	10.38			68.22		
Total heat load of Booster and collider	KW	78.6					

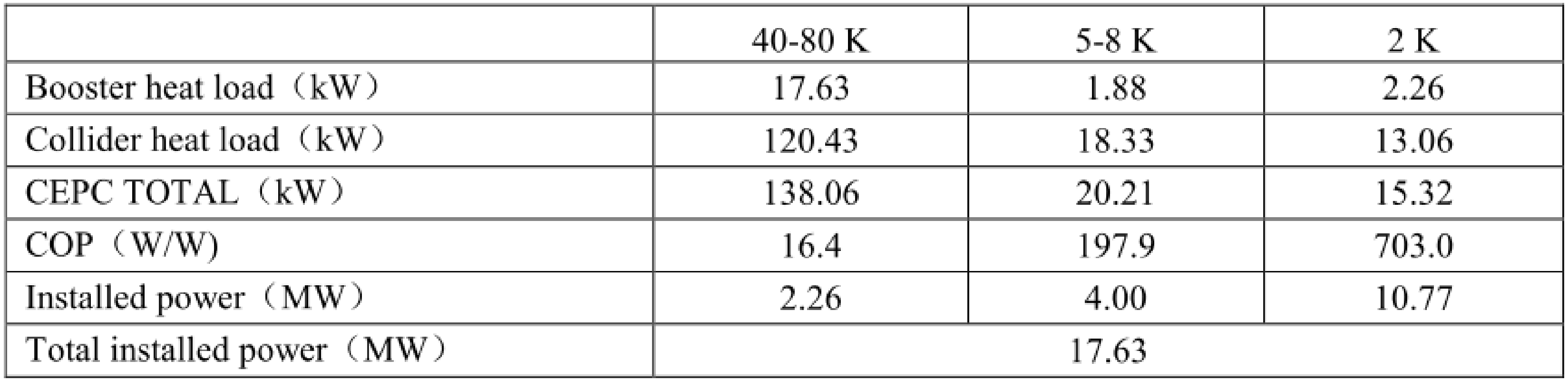
CEPC Cryogenic Efficiency (COP at 4.5 Kdeg)



Improved cryogenic efficiency

Figure 5.3.5: Refrigerator COP at 4.5 K

Table 5.3.3: Cryogenic system installed power requirements



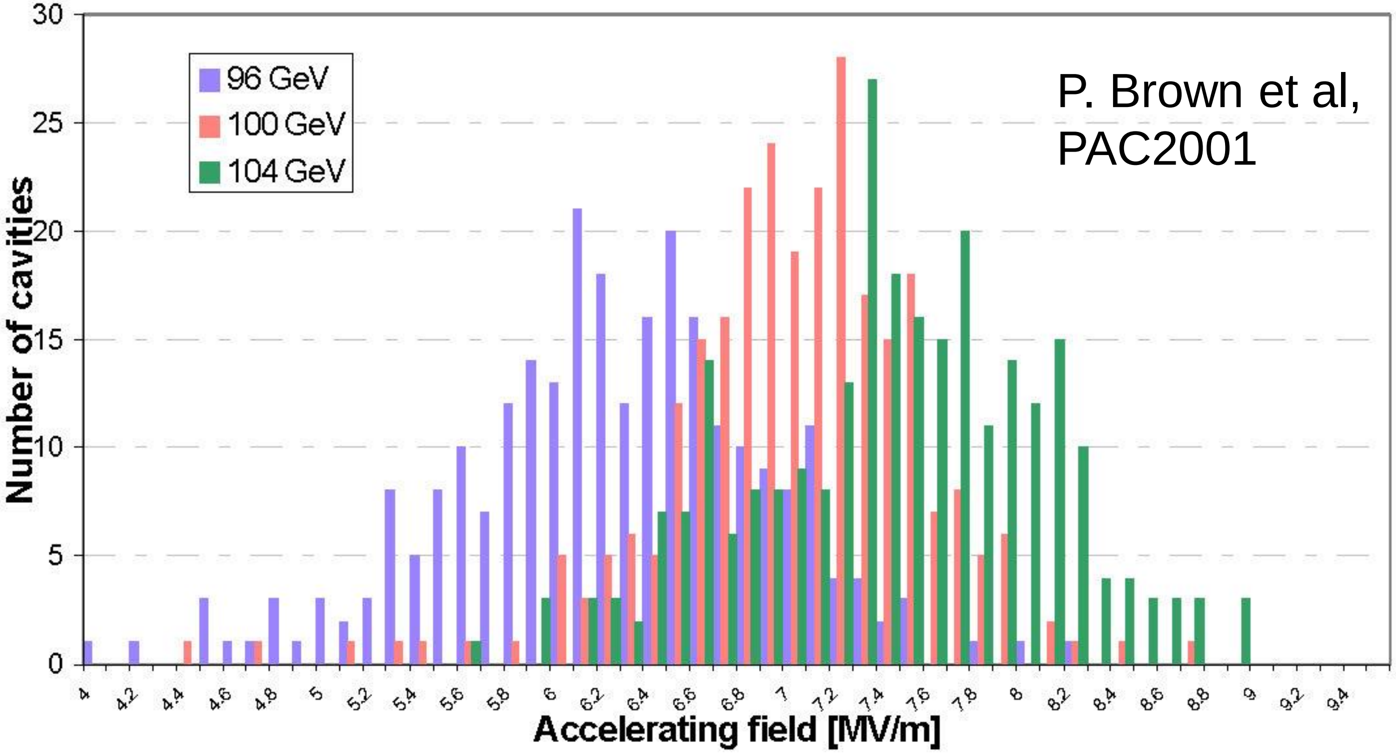
	40-80 K	5-8 K	2 K
Booster heat load（kW）	17.63	1.88	2.26
Collider heat load（kW）	120.43	18.33	13.06
CEPC TOTAL（kW）	138.06	20.21	15.32
COP（W/W)	16.4	197.9	703.0
Installed power（MW）	2.26	4.00	10.77
Total installed power（MW）	17.63		

FCC-ee RF & cryo power (example) (Zimmermann…)

	Z	**W**	**ZH**	**ttbar**
total voltage / beam [GV]	0.2	0.8	3	10
no. cavities / beam	**75**	**150**	**400**	**670**
RF frequency [MHz]	**400**			
cells / cavity	**1**	**2**		
cavity length [m]	0.38	0.75	0.75	0.75
Q_0 [10^9]	**3**	**3**	**3**	**3**
material & temperature	***Nb/Cu* at 4.5K**			
gradient [MV/m]	7.0	7.1	10	10
voltage / cavity [MV]	2.7	5.3	7.5	7.5
input power / cavity [MW]	0.67	0.33	0.125	0.075
R/Q [Ω] linac	87	169		
matched Q_L	$1.3\text{x}10^5$	$5.0\text{x}10^5$	$2.7\text{x}10^6$	$4.4\text{x}10^6$
HOM loss / cavity [kW]	3.1	1.0	0.34	0.16
total HOM power [MW]	**0.5**	**0.3**	**0.3**	**0.22**
dynamic/static cryo power	1, 1	4, 1	20, 3	33, 6
total cryo power [MW]	**2**	**5**	**23**	**39**

Reminder: LEP2 cavities (Zimmermann …)

288 4-cell 352 MHz standing-wave cavities, Nb/Cu at 4.5 K

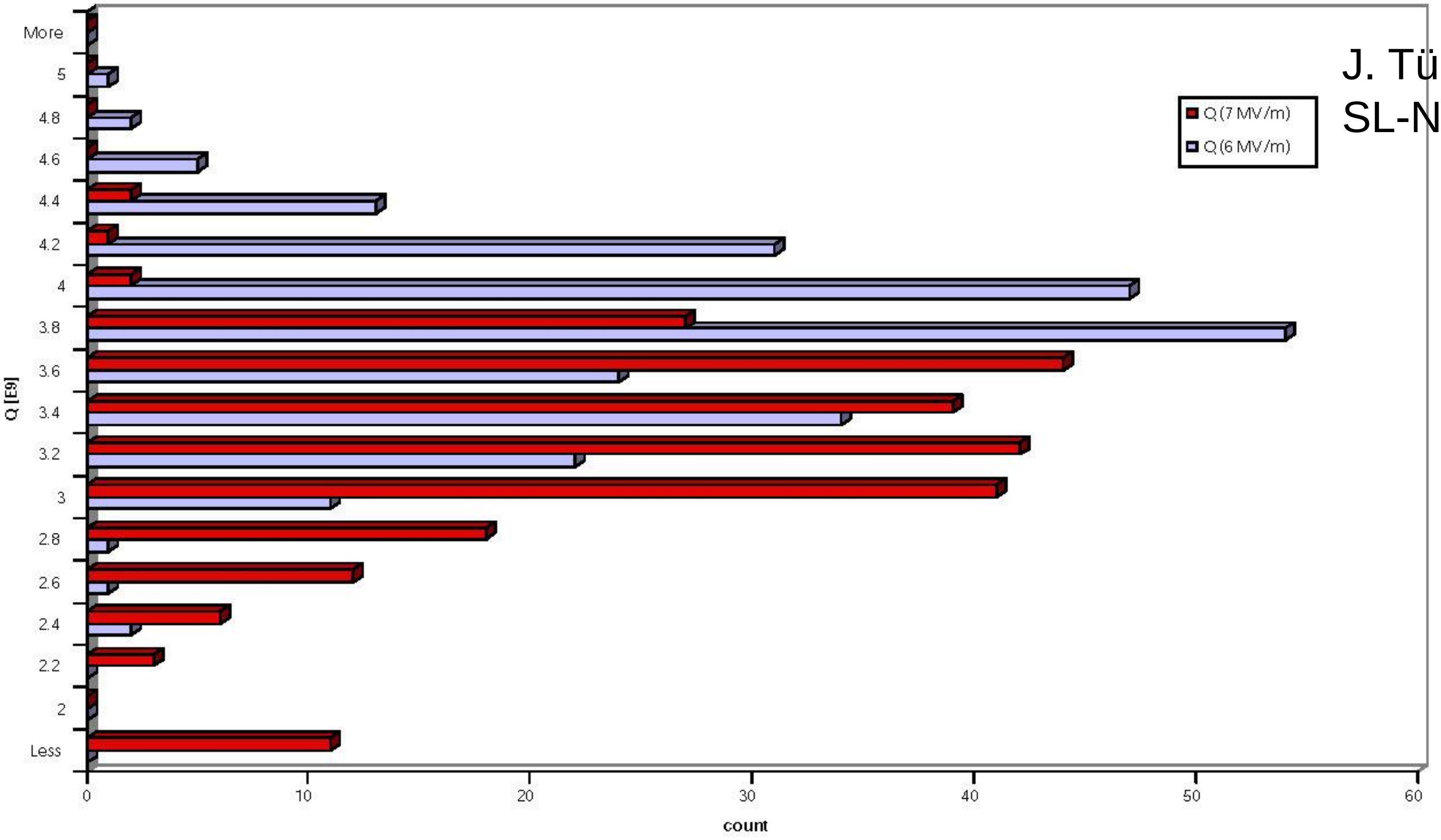


P. Brown et al,
PAC2001

Number of cavities operating at a given gradient for three different beam energies in 1999 and 2000.

Average gradient: 7.5 MV/m (> 6 MV/m nominal)
best cavities 9 MV/m in operation

LEP2 cavities cont'd (Zimmerman …)



J. Tückmantel,
SL-Note-98-076 RF

Histogram of Q-values at 6 and 7 MV/m accelerating gradient

Measured average Q values:
3.7e9 at 6 MV/m
3.1e9 at 7 MV/m

Rough power estimate for FCC-ee [MW] (Zimmermann …)

subsystem	**Z**	**W**	**ZH**	**$t\bar{t}$**	**LEP2** (av.2000*)	**TLEP$t\bar{t}$ * M. Ross**	**TLEP$t\bar{t}$ ** 2013**
collider total RF power	163	163	145	145	42	217	185
collider cryogenics	2	5	23	39	18	41	34
collider magnets	3	10	23	50	16	14	14
booster RF + cryo	4	4	6	7	-	5	5
booster magnets	0	1	2	5	-	-	-
injector complex	10	10	10	10	<10	?	?
physics detectors (2)	10	10	10	10	9	?	?
cooling & ventilation***	47	49	52	62	16	62	26
general services	36	36	36	36	9	20	20
total	275	288	308	364	120	359	284

*dividing total energy used by 200 days

For comparison, total CERN complex in 1998 used up to 237 MW

Rough power estimate for FCC-hh [MW] (Zimmermann …)

subsystem	**FCC-hh**	**LHC** (2015*)
magnet systems (w/o injectors & TLs)	15	5
collider cryogenics	200	36
RF system	12	6
cooling	35	7
ventilation	15	4
general services	40	11
physics experiments (4)	50	21
injector complex	110	60
total	**465 (=110+355)**	**150 (=60+90)**

*P. Lebrun, “Summary of LHC power consumption and scaling to FCC-hh,” FCC IOWG , 29 July 2015

Collider Accelerator Total Power Summary

	PEP-II	SuperB	LEP-2	LHC	CEPC	FCC-ee-ZH	FCC-hh
RF	29	45	42	6	247	145	12
Cryo	0.5	1	18	36	19	23	200
Magnets	6	10	16	5	64	23	15
Cooling	2	2	9	7	41	30	35
Ventilation	0.5	1	7	4	31	20	15
General	2	2	9	11	18	36	40
Detector	2	3	9	21	14	10	50
Injector	8	10	10	60	35	22	110
Total	50	74	120	150	469	308	465

Recent (ongoing) improvements to efficiency

High Q SC cavities

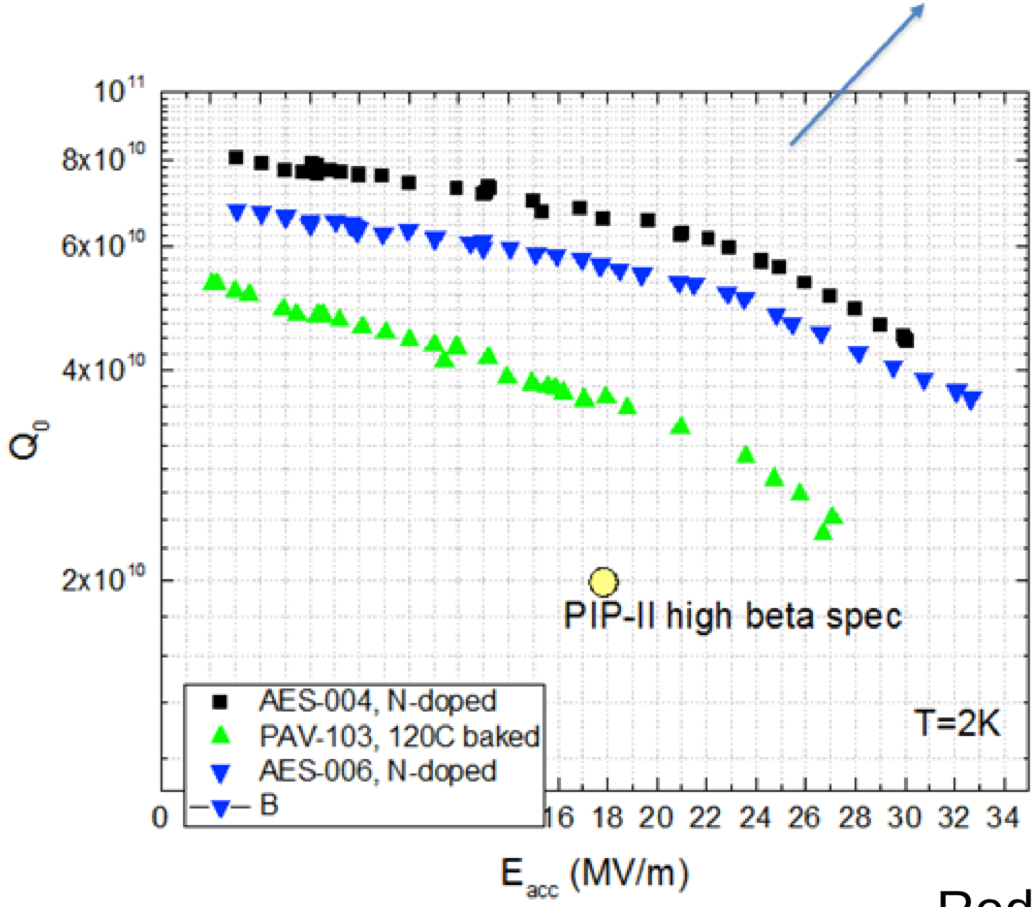
New klystron design

New klystron depressed collector

Longer rings with smaller beam emittances

Improving Q of CW SC Cavities (FNAL, Cornell, JLAB,…)

Applying N doping to 650 MHz (beta=0.9) leads to Q x3 exceeding specs

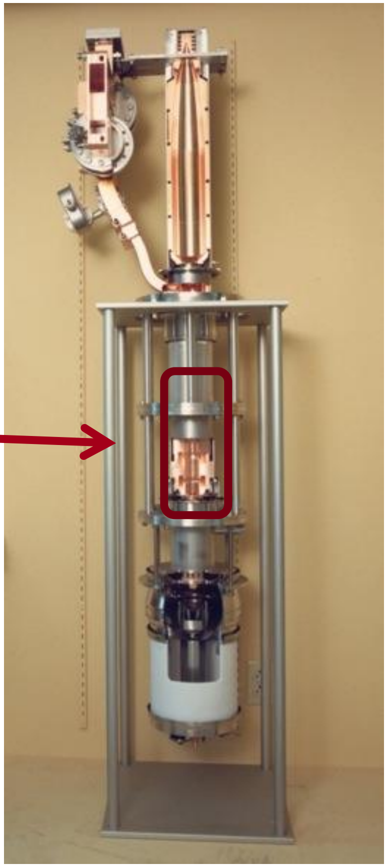


High duty factor operation (30%) may be possible even with the existing (limited) capacity cryoplant!

Reduces cryo-plant requirements

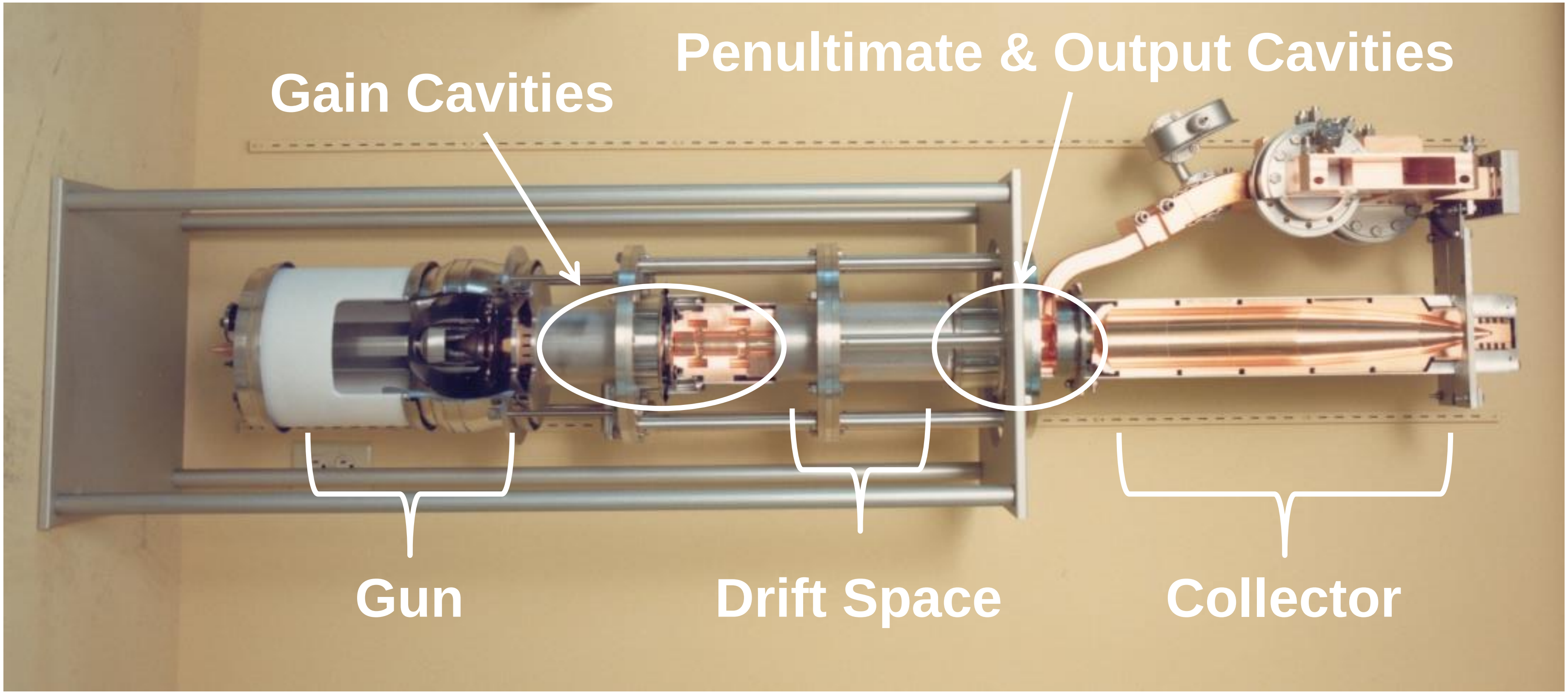
80MW 55% Efficient S-Band Source (Jensen, Neilson)(SLAC)

- Increase RF output power of the 5045 from 60MW to 80MW
- Increase RF efficiency of the 5045 from 45% to 55%
- Add 4 new RF cells to the body design
- Add a new high power RF window
- Modified tube "plug compatible" with existing socket
- Test modules under construction



SLAC 5045
60MW S-band tube

Project Scope - Existing 5045 Klystron



Depressed Collector Klystron (Kemp, Jensen, Neilson) (SLAC)

Old idea but with new applications (SLAC new study)

Depressed collector klystrons can improve power efficiency for both CW and pulsed accelerators

Reduced heat loading

Reduces parasitic emitted radiation

New: Allows improved modulator pulse shape

New: Uses feedforward energy recovery system

New: Multiple anodes with self powering (voltage)

Modeled by 2D PIC codes

45% → 57% efficient

Model under construction (80 MW, 55%, 2856 MHz)

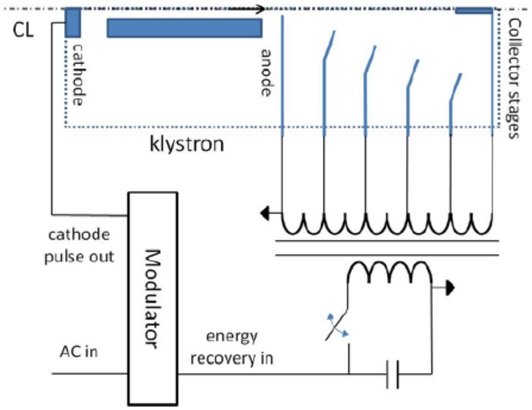
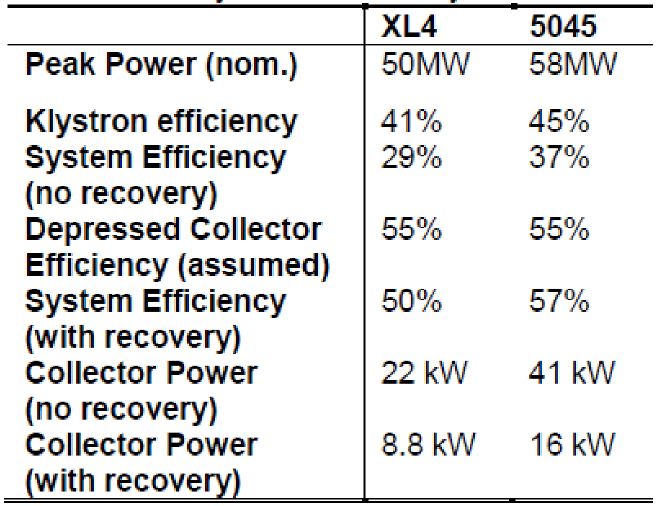


Figure 1. Block diagram of a pulsed depressed collector.

Table 1. Calculated improvements in system efficiency for two SLAC klystrons.



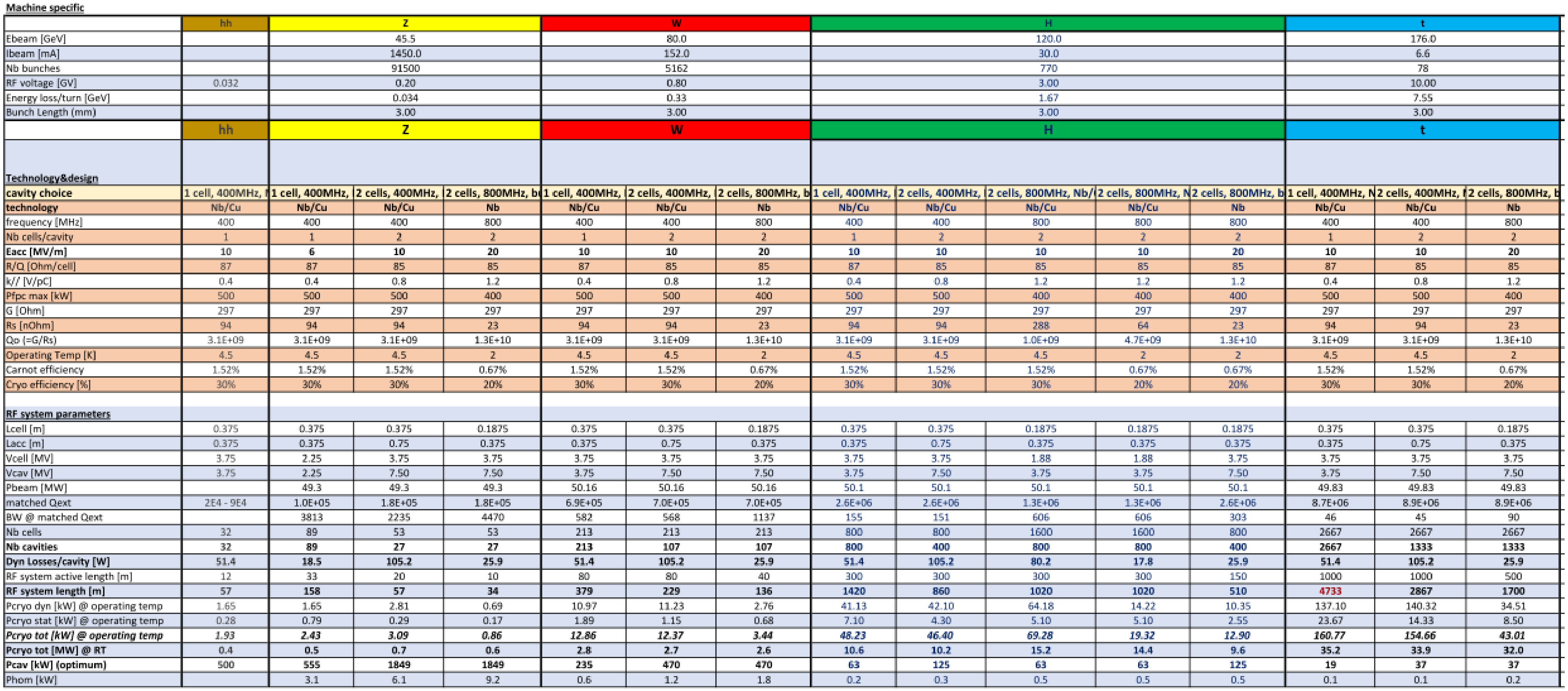
	XL4	5045
Peak Power (nom.)	50MW	58MW
Klystron efficiency	41%	45%
System Efficiency (no recovery)	29%	37%
Depressed Collector Efficiency (assumed)	55%	55%
System Efficiency (with recovery)	50%	57%
Collector Power (no recovery)	22 kW	41 kW
Collector Power (with recovery)	8.8 kW	16 kW

Conclusions

Ongoing efforts to increase accelerator efficiency:

- Larger rings are more efficient with lower RF and emittances but cost more to build
- Improved cavity Qs
- Improved higher efficiency klystrons (cw)
- Depressed collectors (pulsed, cw)
- Improved Solid State Amplifiers
- Improved cryo-plants for better cryo energy usage

FCC Specific Issues for Power (Zimmermann …)



Machine specific

	hh	Z			W			H					t		
Ebeam [GeV]		45.5			80.0			120.0					176.0		
Ibeam [mA]		1450.0			152.0			30.0					6.6		
Nb bunches		91500			5162			770					78		
RF voltage [GV]	0.032	0.20			0.80			3.00					10.00		
Energy loss/turn [GeV]		0.034			0.33			1.67					7.55		
Bunch Length (mm)		3.00			3.00			3.00					3.00		
	hh	**Z**			**W**			**H**					**t**		
Technology&design															
cavity choice	1 cell, 400MHz,	**1 cell, 400MHz,**	**2 cells, 400MHz,**	**2 cells, 800MHz, b**	**1 cell, 400MHz,**	**2 cells, 400MHz,**	**2 cells, 800MHz, b**	**1 cell, 400MHz,**	**2 cells, 400MHz,**	**2 cells, 800MHz, Nb/**	**2 cells, 800MHz, N**	**2 cells, 800MHz, b**	**1 cell, 400MHz, N**	**2 cells, 400MHz,**	**2 cells, 800MHz, b**
technology	Nb/Cu	**Nb/Cu**	**Nb/Cu**	**Nb**	**Nb/Cu**	**Nb/Cu**	**Nb**	**Nb/Cu**	**Nb/Cu**	**Nb/Cu**	**Nb/Cu**	**Nb**	**Nb/Cu**	**Nb/Cu**	**Nb**
frequency [MHz]	400	400	400	800	400	400	800	400	400	800	800	800	400	400	800
Nb cells/cavity	1	1	2	2	1	2	2	1	2	2	2	2	1	2	2
Eacc [MV/m]	**10**	**6**	**10**	**20**	**10**	**10**	**20**	**10**	**10**	**10**	**10**	**20**	**10**	**10**	**20**
R/Q [Ohm/cell]	87	87	85	85	87	85	85	87	85	85	85	85	87	85	85
k// [V/pC]	0.4	0.4	0.8	1.2	0.4	0.8	1.2	0.4	0.8	1.2	1.2	1.2	0.4	0.8	1.2
Pfpc max [kW]	500	500	500	400	500	500	400	500	500	400	400	400	500	500	400
G [Ohm]	297	297	297	297	297	297	297	297	297	297	297	297	297	297	297
Rs [nOhm]	94	94	94	23	94	94	23	94	94	288	64	23	94	94	23
Qo (=G/Rs)	3.1E+09	3.1E+09	3.1E+09	1.3E+10	3.1E+09	3.1E+09	1.3E+10	3.1E+09	3.1E+09	1.0E+09	4.7E+09	1.3E+10	3.1E+09	3.1E+09	1.3E+10
Operating Temp [K]	4.5	4.5	4.5	2	4.5	4.5	2	4.5	4.5	4.5	2	2	4.5	4.5	2
Carnot efficiency	1.52%	1.52%	1.52%	0.67%	1.52%	1.52%	0.67%	1.52%	1.52%	1.52%	0.67%	0.67%	1.52%	1.52%	0.67%
Cryo efficiency [%]	30%	30%	30%	20%	30%	30%	20%	30%	30%	30%	20%	20%	30%	30%	20%
RF system parameters															
Lcell [m]	0.375	0.375	0.375	0.1875	0.375	0.375	0.1875	0.375	0.375	0.1875	0.1875	0.1875	0.375	0.375	0.1875
Lacc [m]	0.375	0.375	0.75	0.375	0.375	0.75	0.375	0.375	0.75	0.375	0.375	0.375	0.375	0.75	0.375
Vcell [MV]	3.75	2.25	3.75	3.75	3.75	3.75	3.75	3.75	3.75	1.88	1.88	3.75	3.75	3.75	3.75
Vcav [MV]	3.75	2.25	7.50	7.50	3.75	7.50	7.50	3.75	7.50	3.75	3.75	7.50	3.75	7.50	7.50
Pbeam [MW]		49.3	49.3	49.3	50.16	50.16	50.16	50.1	50.1	50.1	50.1	50.1	49.83	49.83	49.83
matched Qext	2E4 - 9E4	1.0E+05	1.8E+05	1.8E+05	6.9E+05	7.0E+05	7.0E+05	2.6E+06	2.6E+06	1.3E+06	1.3E+06	2.6E+06	8.7E+06	8.9E+06	8.9E+06
BW @ matched Qext		3813	2235	4470	582	568	1137	155	151	606	606	303	46	45	90
Nb cells	32	89	53	53	213	213	213	800	800	1600	1600	800	2667	2667	2667
Nb cavities	**32**	**89**	**27**	**27**	**213**	**107**	**107**	**800**	**400**	**800**	**800**	**400**	**2667**	**1333**	**1333**
Dyn Losses/cavity [W]	51.4	**18.5**	**105.2**	**25.9**	**51.4**	**105.2**	**25.9**	**51.4**	**105.2**	**80.2**	**17.8**	**25.9**	**51.4**	**105.2**	**25.9**
RF system active length [m]	12	33	20	10	80	80	40	300	300	300	300	150	1000	1000	500
RF system length [m]	57	**158**	**57**	**34**	**379**	**229**	**136**	**1420**	**860**	**1020**	**1020**	**510**	**4733**	**2867**	**1700**
Pcryo dyn [kW] @ operating temp	1.65	1.65	2.81	0.69	10.97	11.23	2.76	41.13	42.10	64.18	14.22	10.35	137.10	140.32	34.51
Pcryo stat [kW] @ operating temp	0.28	0.79	0.29	0.17	1.89	1.15	0.68	7.10	4.30	5.10	5.10	2.55	23.67	14.33	8.50
Pcryo tot [kW] @ operating temp	*1.93*	***2.43***	***3.09***	***0.86***	***12.86***	***12.37***	***3.44***	***48.23***	***46.40***	***69.28***	***19.32***	***12.90***	***160.77***	***154.66***	***43.01***
Pcryo tot [MW] @ RT	0.4	**0.5**	**0.7**	**0.6**	**2.8**	**2.7**	**2.6**	**10.6**	**10.2**	**15.2**	**14.4**	**9.6**	**35.2**	**33.9**	**32.0**
Pcav [kW] (optimum)	500	**555**	**1849**	**1849**	**235**	**470**	**470**	**63**	**125**	**63**	**63**	**125**	**19**	**37**	**37**
Phom [kW]		3.1	6.1	9.2	0.6	1.2	1.8	0.2	0.3	0.5	0.5	0.5	0.1	0.1	0.2