RF Power Sources for ERLs

W. Anders, HZB, ERL 2011, Tsukuba

Outline

- RF power budget
- High power RF system architecture
- RF Power sources
- Klystron vs IOT vs solid state amplifier

- RF systems at specific projects

RF power budget

P_{RF} = **Beam loading**

energy gain · effective beam current
main contribution at high current accelerators

ERL: >10^{-4} energy recovery eff. ➔ effective current low

+ Cavity losses

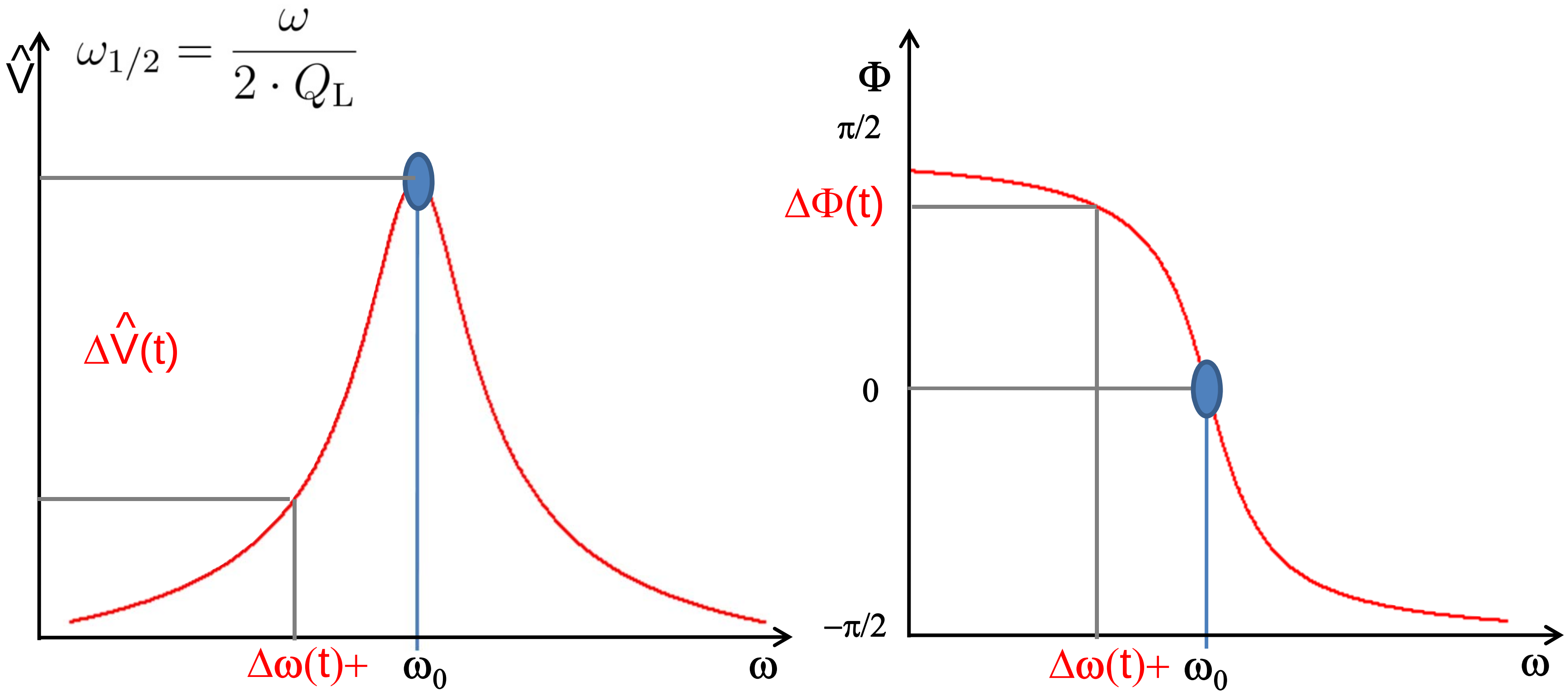
small for sc cavities 1-30 W

+ losses in transmission lines

typical 25-30 %

+ headroom for microphonic detuning

RF power budget -- microphonics



- Detuning → Phase and amplitude variation
- **Compensation by phase shift and extra power**
- Strong detuning → Energy modulation of the beam

RF power budget

P_{RF} = **beam loading**

energy gain · effective beam current
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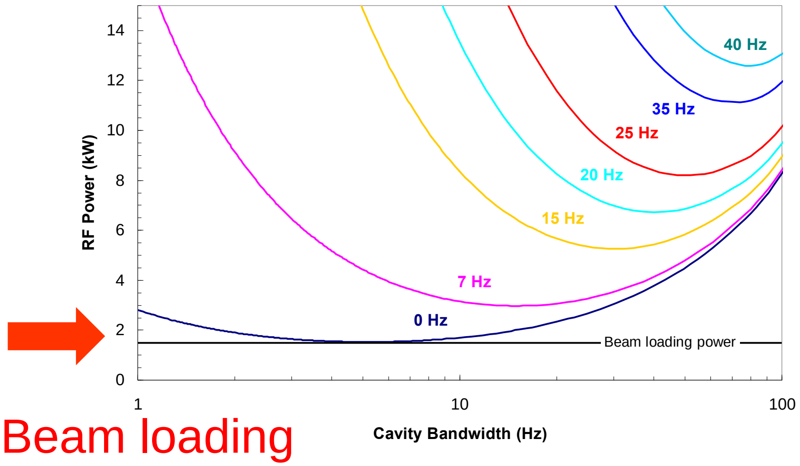
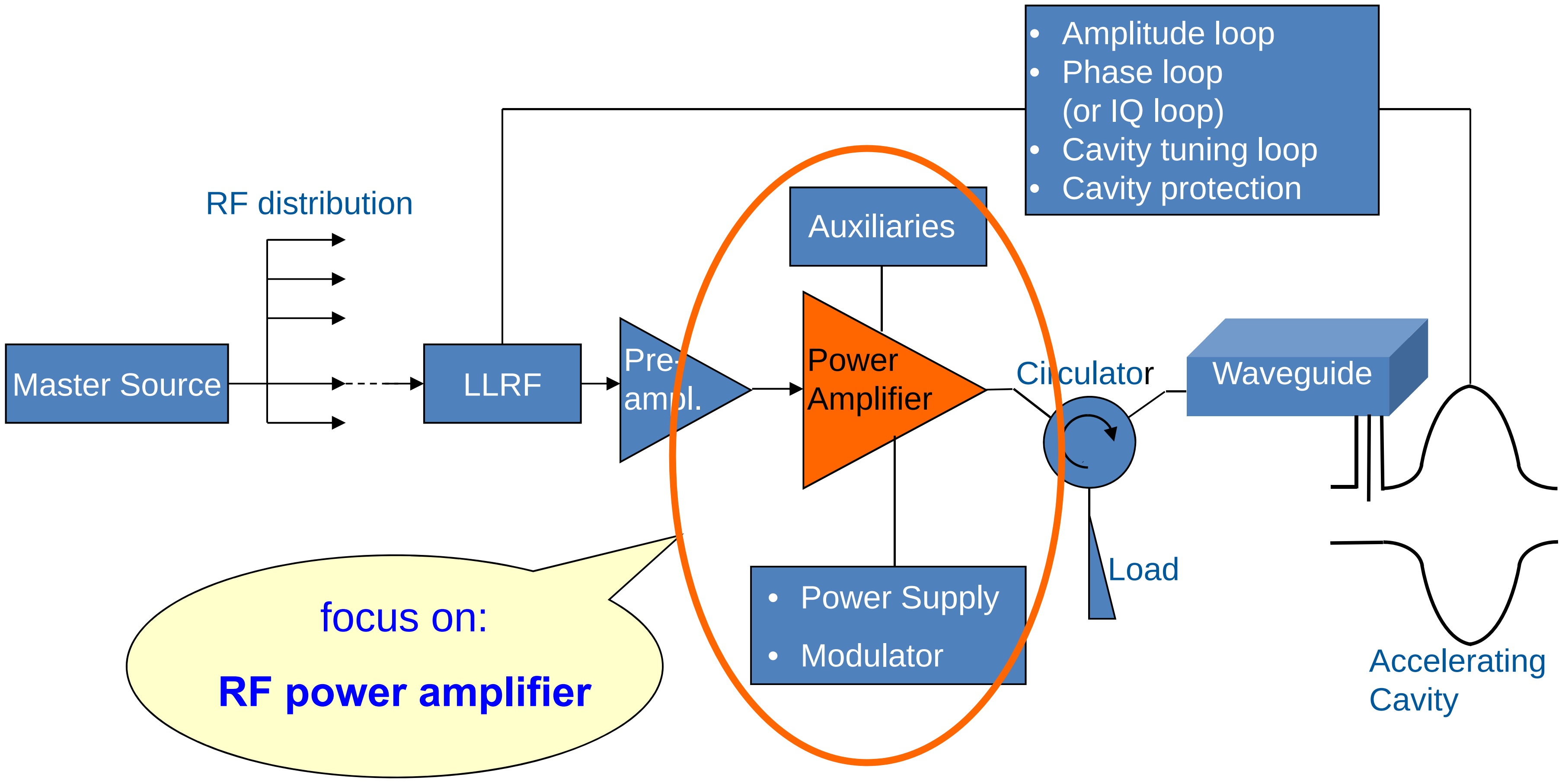


main contribution to power level at cw operated FEL and ERL main linac
sc cavities are operated at 10-30 Hz bandwidth and detuning due to microphonics has to be compensated by RF power

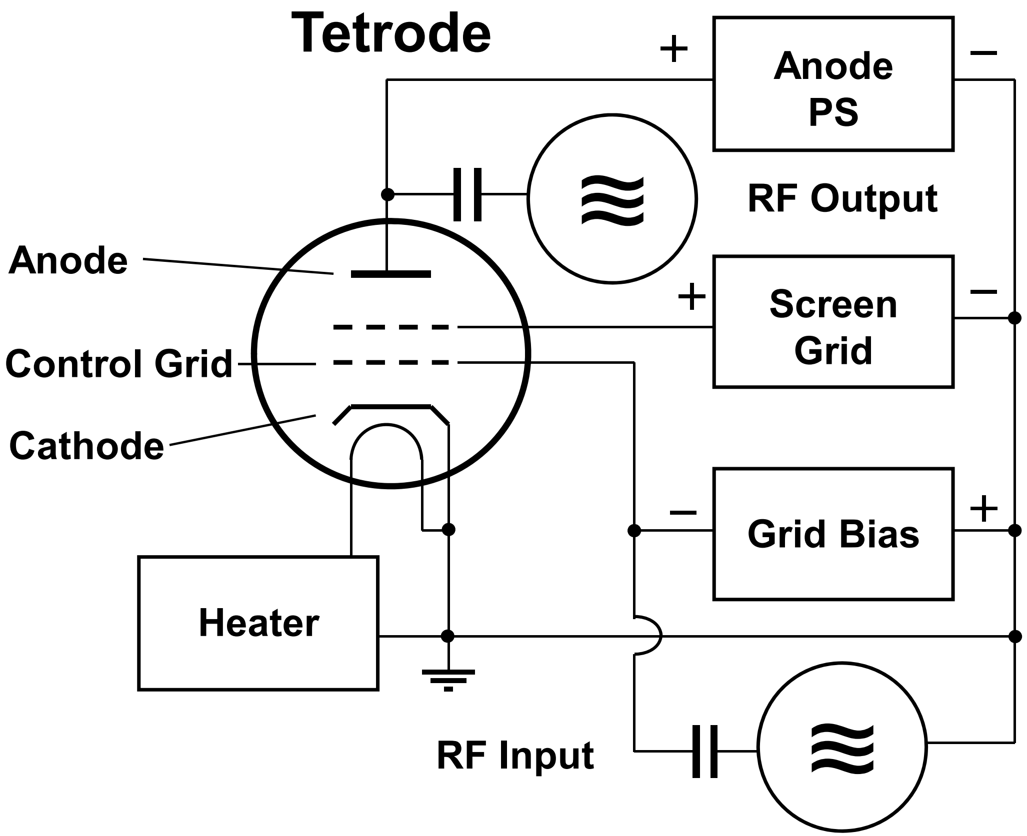
RF power versus cavity bandwidth for different microphics levels at a system with 1.5 kW beam loading

Typical setup of a RF transmitter



J. Jacob

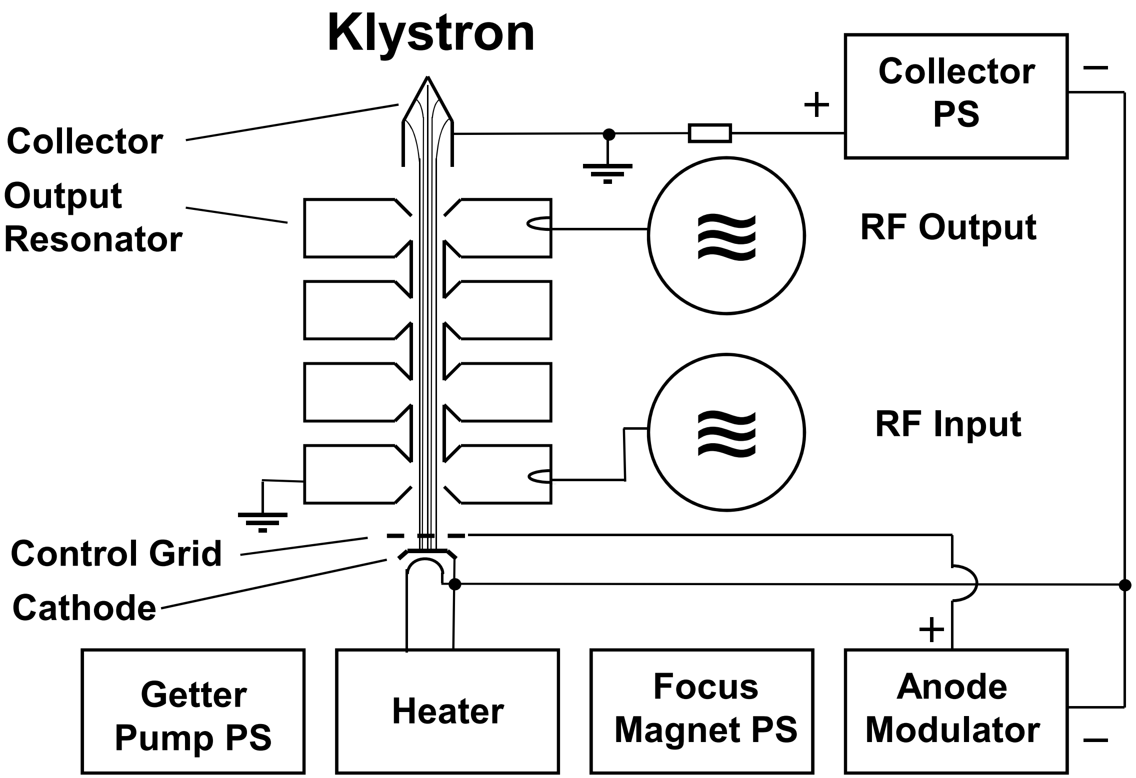
RF power generation: Tetrode



Tetrode:

- Intensity modulation of DC beam by control grid
- Roubust
- Typical up to 400 MHz
- High power → MW´s

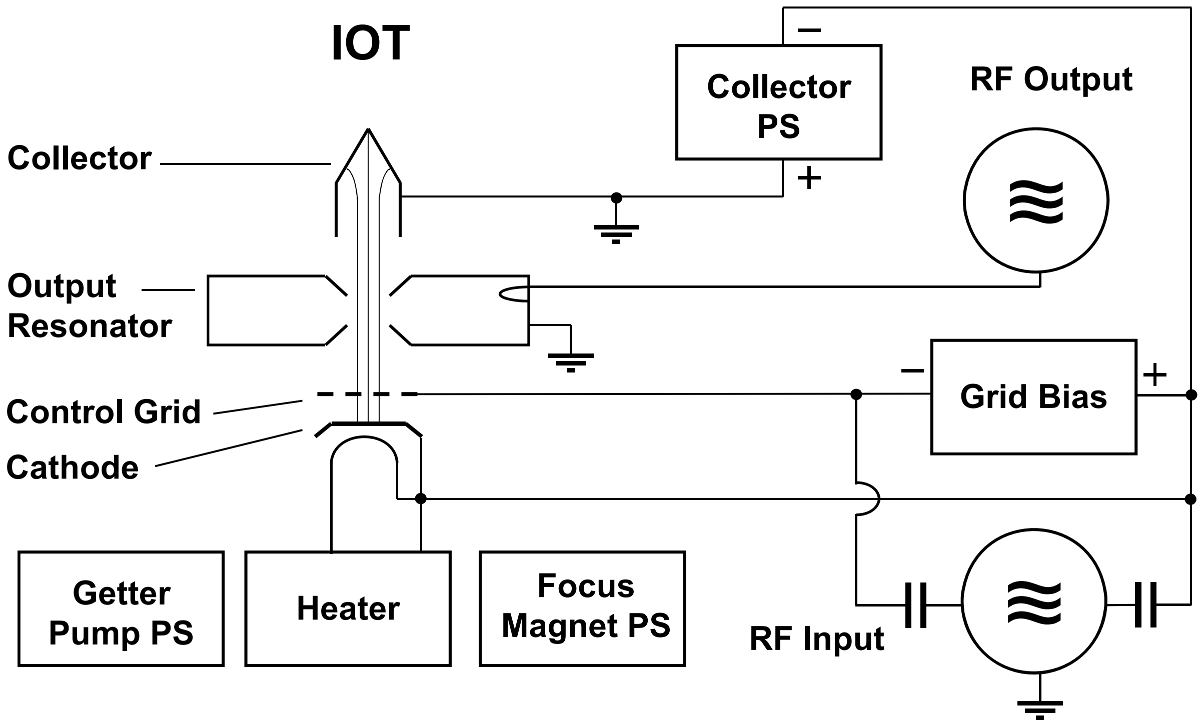
RF power generation: Klystron



Klystron:

- Intensity modulation of DC beam by cavity
- Output cavity
- Typical 300 MHz – 30 GHz
- High power → MW´s
- High gain

RF power generation: IOT

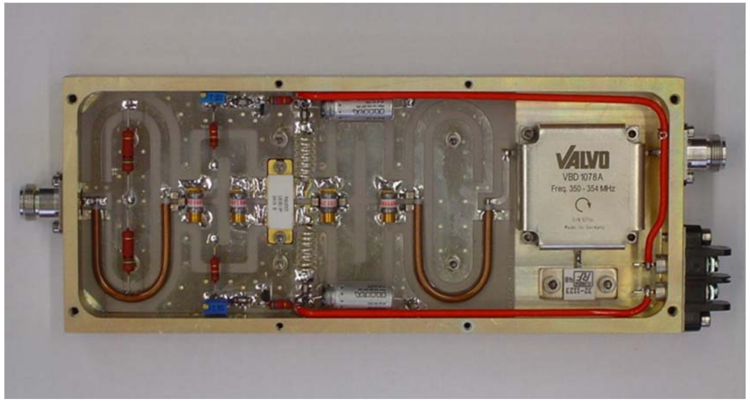


IOT:

- Intensity modulation of DC beam by control grid
- up to 1300 MHz
- moderate power (<100 kW)

Architecture of a 350 MHz 180 kW solid state amplifier (I)

HZB Helmholtz Zentrum Berlin



315 W power module

28 V 600 W DC/DC converter

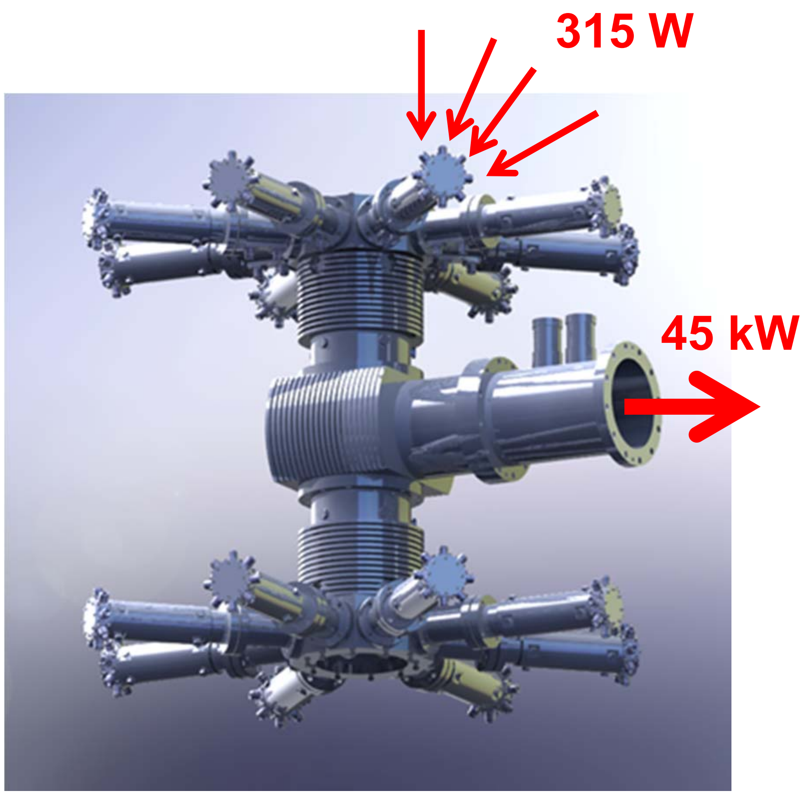
10 x power combiner

2.5 kW **25 kW** **100 kW** **200 kW**

Ti Ruan

Architecture of a 350 MHz 180 kW solid state amplifier (II)

HZB Helmholtz Zentrum Berlin



160 way power combiner (AREVA)

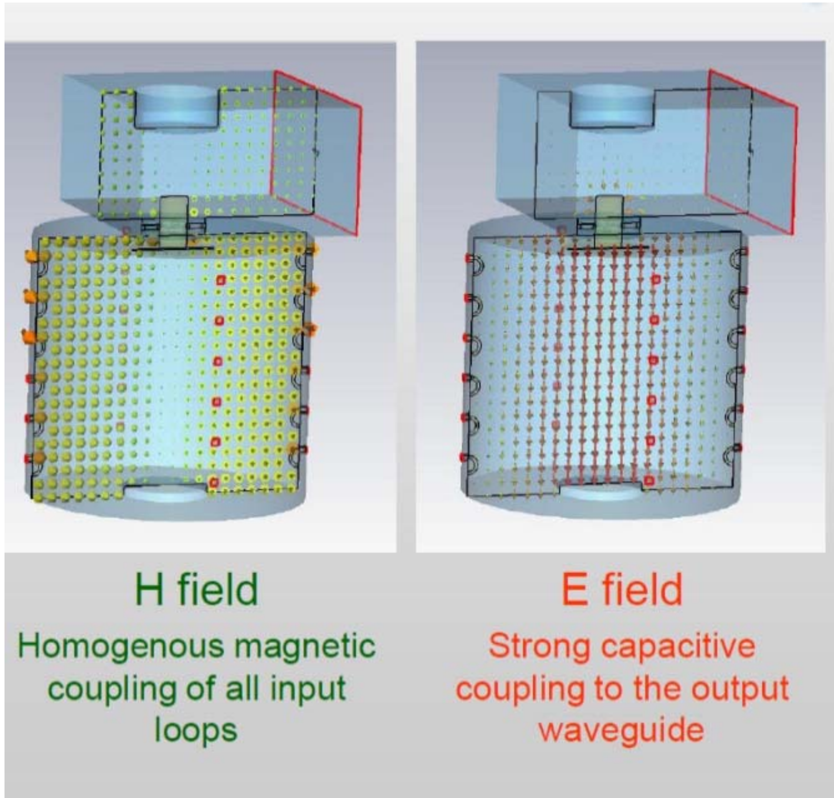
180 kW 350 MHz solid state amplifier, each column 45 kW (Soleil)

total 640 modules !!

in case of single module failure, no trip → 20,000 h operation -- no trip !!

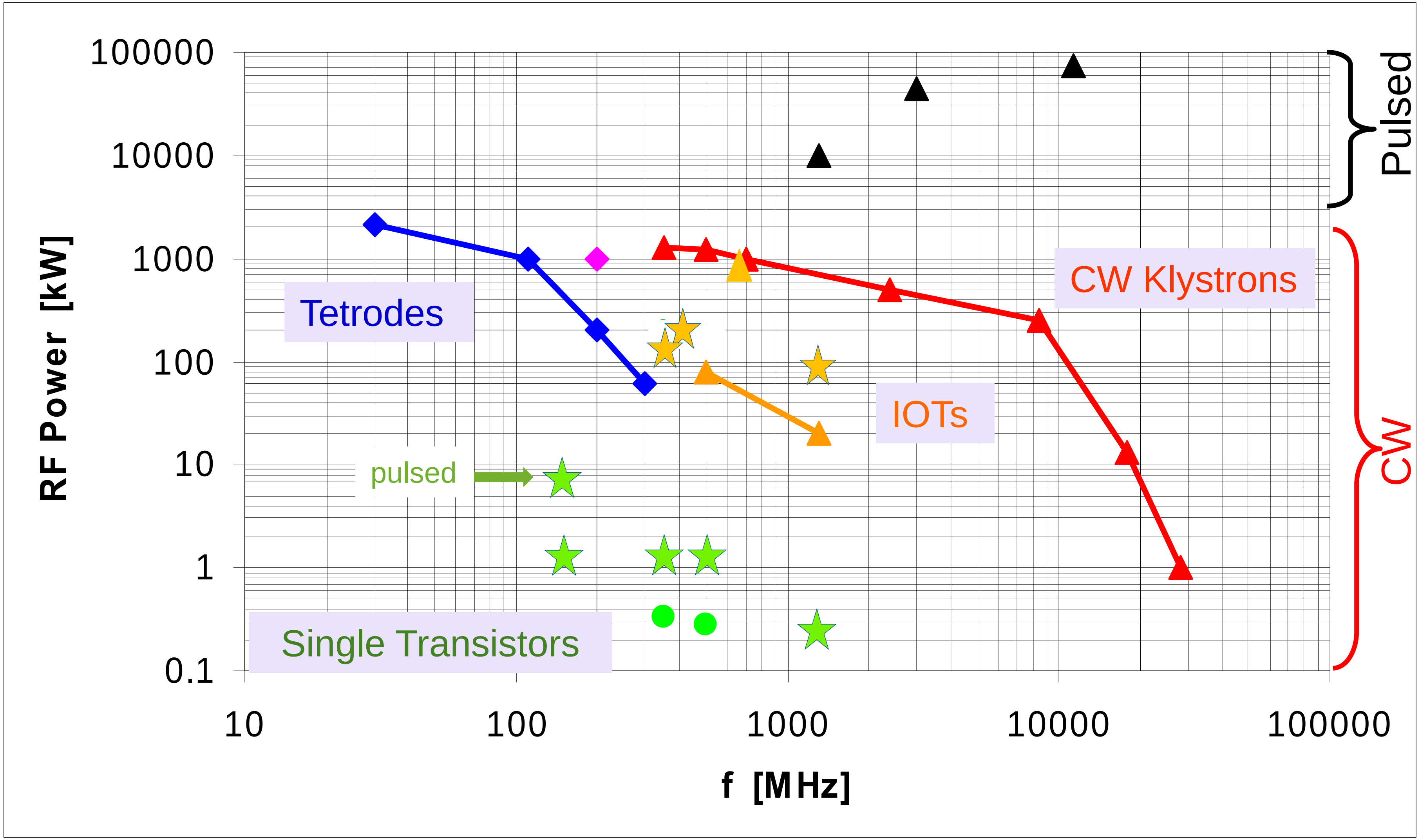
Solid State Amplifiers – new developments

Cavity combiner
to sum up power of 120 RF modules in one device (Jörn Jacob)



Prototyp of a cavity combiner

Power sources

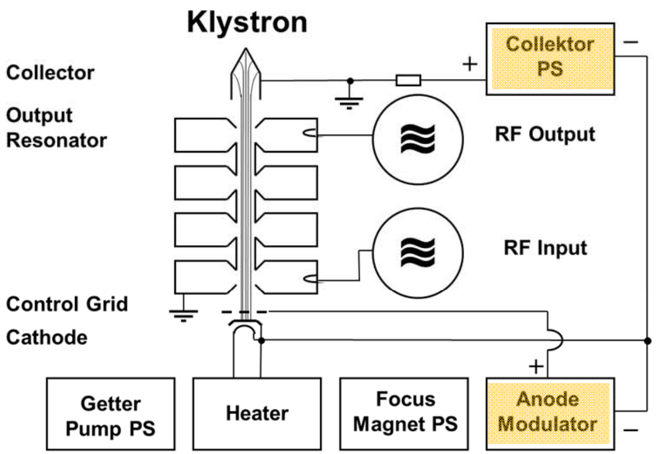


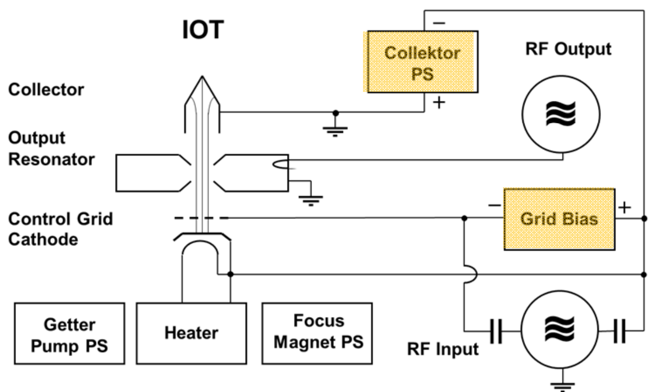
Klystron vs IOT vs solid state amplifier

UHF and L-Band

	Klystron	IOT	Solid state
Power level	Up to MW	< 100 kW but R&D for higher level ongoing	200 W-1 kW single transistor, sum it up
Efficiency	High efficiency in saturation, which drops rapidly at reduced power Class A operation	High efficiency, which does not drop quickly at reduced power. Class B operation	High < 800 MHz to moderate >800 MHz Class B operation
Gain	High gain (> 40 dB)	Low gain ~22 dB	Low gain 15-25 dB
Operating voltage	High voltage 20 kV ... 200 kV	High voltage 20 kV ... 200 kV	28 / 50 / 700 V
Reliabillity	normal	normal	High
Maintainabillity	Poor HV installation	Poor HV installation	Very good Hot plugged modules
Expandabillity	poor	poor	good
Size	Long, many cavities	Short, one cavity	Hundrets of small modules

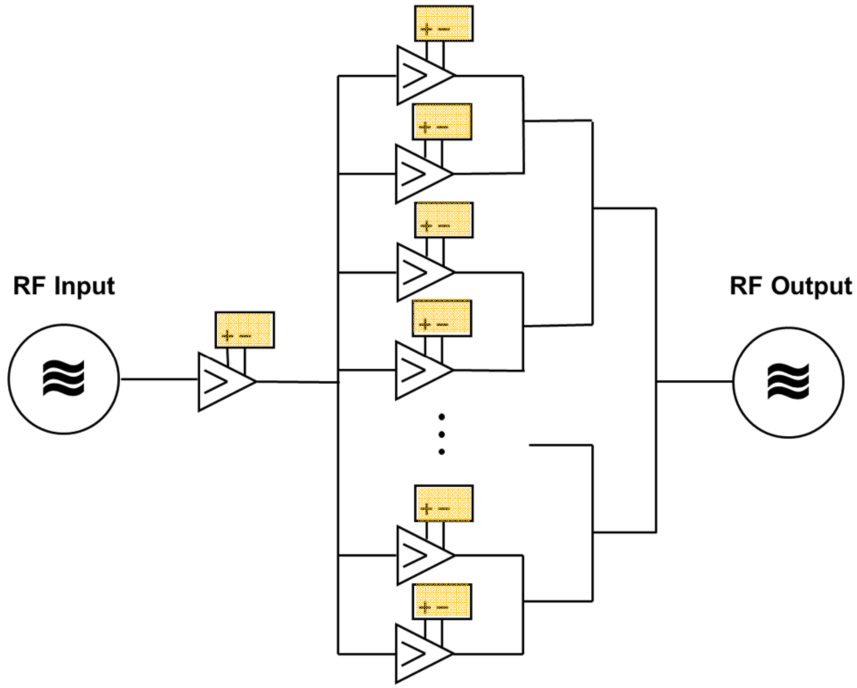
Architecture of klystron / IOT / solid state power sources





Special FEL and ERL accelerators need very high stability of RF transmitters
Phase stabiltiy < 0.1 deg (0.01 deg!!)
Amplitude stability < 0.1 %

Careful specification of main power supplies is essential



Low noise transmitters at HZB

HZB Helmholtz Zentrum Berlin


HoBiCaT at HZB

IOT 16 (25) kW_{cw} 1.3 GHz
Anode PS:
31 kV 1,3 A Stability < $1 * 10^{-4}_{pp}$
Bias PS:
150 V ± 300 mA < $2 * 10^{-4}_{pp}$

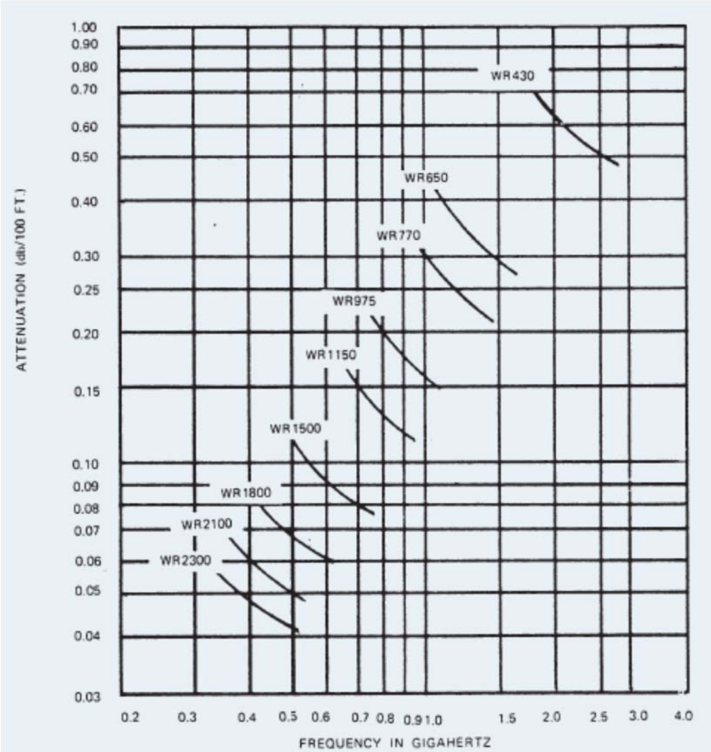
➔ RF amplitude noise: < $2 * 10^{-4}_{pp}$
➔ RF phase noise: < $0.1°_{pp}$

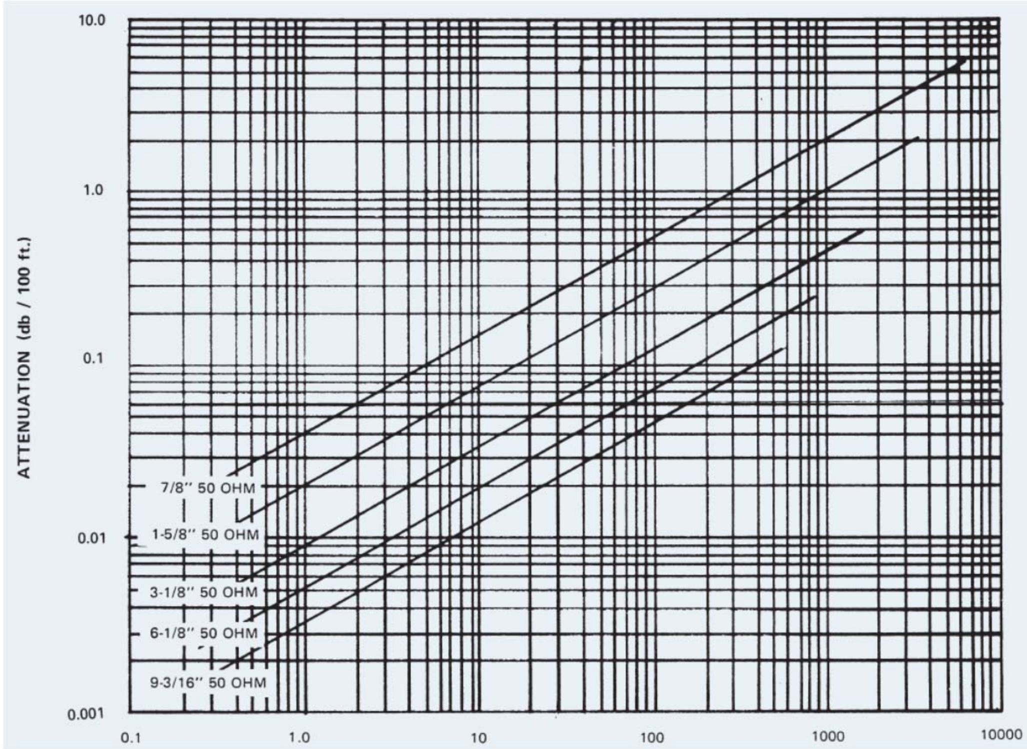
0.008° with closed loop

MLS operated by HZB

IOT 80 kW_{cw} 500 MHz
Anode PS:
37 kV 3.8 A Stability < $5 * 10^{-4}_{pp}$
Bias:
250 V ± 300 mA < $1 * 10^{-3}_{pp}$

NextTransmitter
B*ERL*inPro injector:
Klystron 300 kW_{cw} 1.3 GHz
50 (60) kV   10 (8) A





***<u>VHF to UHF frequencies</u>*:**

Coaxial transmission lines, losses increase as √f

***<u>UHF and higher</u>*:**

Waveguides, losses increase as ~f^3/2 as in addition to skin depth decrease one has to use smaller and smaller size waveguides

Applying the lessons learned

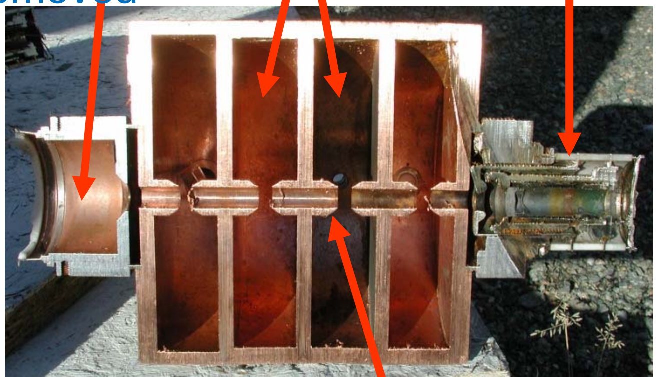
Examples RF Installations

Projects: CEBAF

Host: JLAB (Newport News)
Application:
Frequencies: 1500 MHz
Superconducting cavities
Transmitter power: 338 x 5/6.5 kW klystron
MTBF: 148.000 h
Stability: 0.5° phase 0.045% amplitude

Project status: operating since 1990

Collector removed Cavities Gun



Drift Tubes

(T. Powers) Crossection of klystron

Inside a transmitter: 8 klystron (4 to be seen) powered by one power supply

Projects: JLAB ERL

Host: JLAB (Newport News)
Application: IR/UV ERL

Frequencies: 1500 MHz
Superconducting cavities
Transmitter power: 24 x 8 kW klystron
2 x 100 kW klystron
Stability: 0.5° phase 0.045% amplitude

Project status: operating

100 kW klystron

(T. Powers)

Host: BNL (Bookhaven)
Application: ERL high current coolerERL (50/500 mA !!)

Frequencies: 704 MHz
Superconducting cavities
Transmitter power: **50 kW IOT (main linac)**
1 MW klystron Injector

Project status: in installation

50 kW IOT transmitter

1 MW klystron

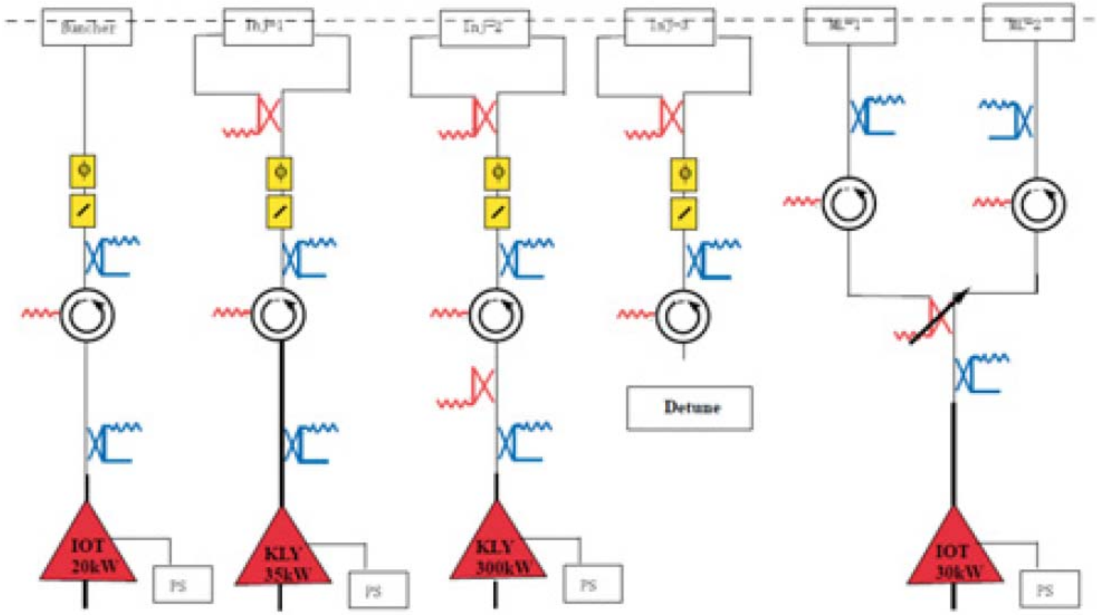
(S. Belomestnykh)

Projects: cERL

Host: KEK (Tsukuba)
Application: ERL demonstrator for light source (35 MeV)

Frequencies: 1300 MHz
Superconducting cavities
Transmitter power: 1 x 300 kW_{cw} Klystron
1 x 35 kW_{cw} Klystron
1 x 30 kW_{cw} IOT
1 x 20 kW_{cw} IOT

Project status: construction phase



(S. Fukuda, IPAC 2010)

Novosibirsk ERL based FEL

Host: Budker Institut (Novosibisrk)
Application: ERL for FEL

Frequencies: 180 MHz
Normalconducting cavities
Transmitter power: **2x 60 kW Tetrode (Injector)**
2x 500 kW by 4 Tetrodes each (Linac)

Project status: in operation (2003)

500 kW Tetrode transmitter

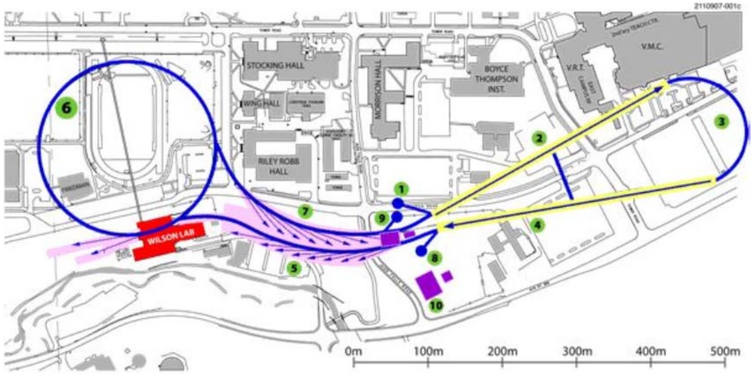
(A. Matveenko)

Projects: Cornell ERL

Host: Cornell University (Ithaca)
Application: ERL light source

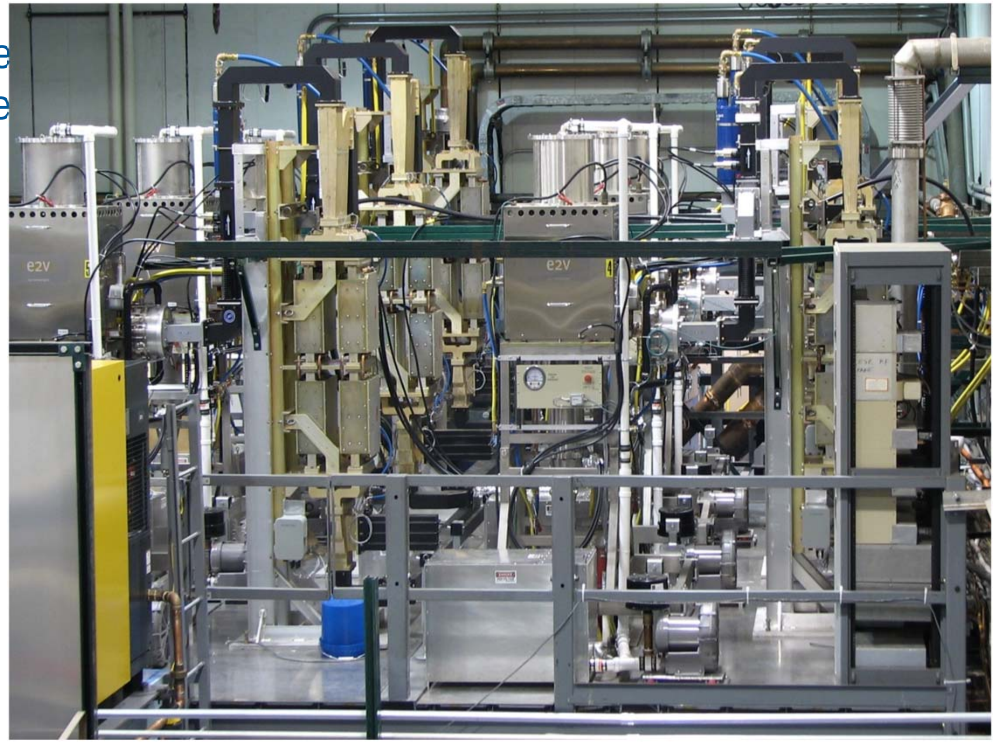
Frequencies: 1300 MHz
Transmitter power: 5 x 135 kW_{cw} klystron operating at injector
12 x 135 kW_{cw} klystron planned
384 x 5 kW_{cw} planned
Stability: (inj) 0.1° phase 0.1% amplitude
linac: 0.05° phase 0.01% amplitude

Project status: injector operating,
Cornell ERL planned



Expanding CESR to the Cornell ERL

(S. Belomestnykh)



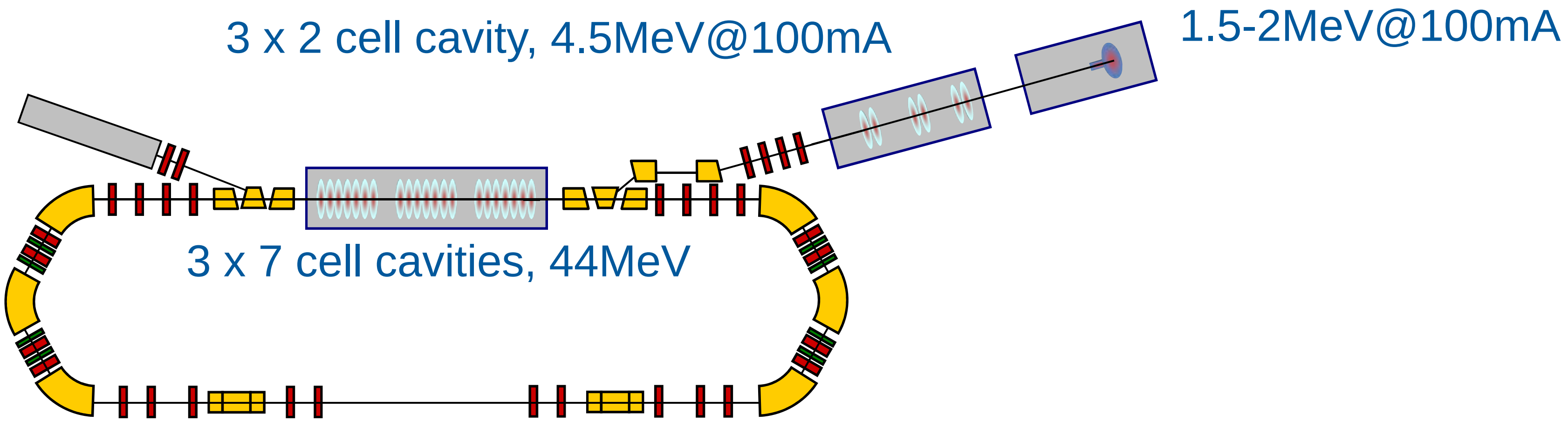
5 x 135 kW 1.3 GHz klystron transmitter

Projects: BERLinPro

Host: HZB (Helmholtz Zentrum Berlin)
Application: ERL demonstrator (100 MeV)

Frequency: 1300 MHz
Superconducting cavities
Transmitter power: 4 x **15 kW$_{cw}$ solid state** (3x linac, 1x booster)
3 x **270 kW$_{cw}$ klystron (linear range)** for booster and gun
Stability: 0.1° phase 0.1% amplitude

Project status: construction phase 2011-2015



Data of B*ERL*inPro

Laboratory : HZB   Project : B*ERL*inPro

Beam Energy : 50 MeV
Beam current: 100 mA
RF frequency:1.3 GHz
cw or pulse: cw   rep. rate: --

RF parameters

Injector linac

- Beam energy: 6.5 MeV
- Number of cavities: 3+1 (Booster + Gun)
- Number of cells per cavity: 2 + 0,6/1,6
- Accelerating gradient: 9MV/m +20 MV/m
- Qext of power coupler: 5E4
- RF power per coupler: 100 kW 2 coupler/cav

Main linac

- total number of cavities: 3
- number of cavities per module: 3
- number of cell per cavity:7
- accelerating gradient: 19 MV/m
- Qext of power coupler: ~ 5E7
- RF power per cavity: 15 kW
- HOM load: waveguide