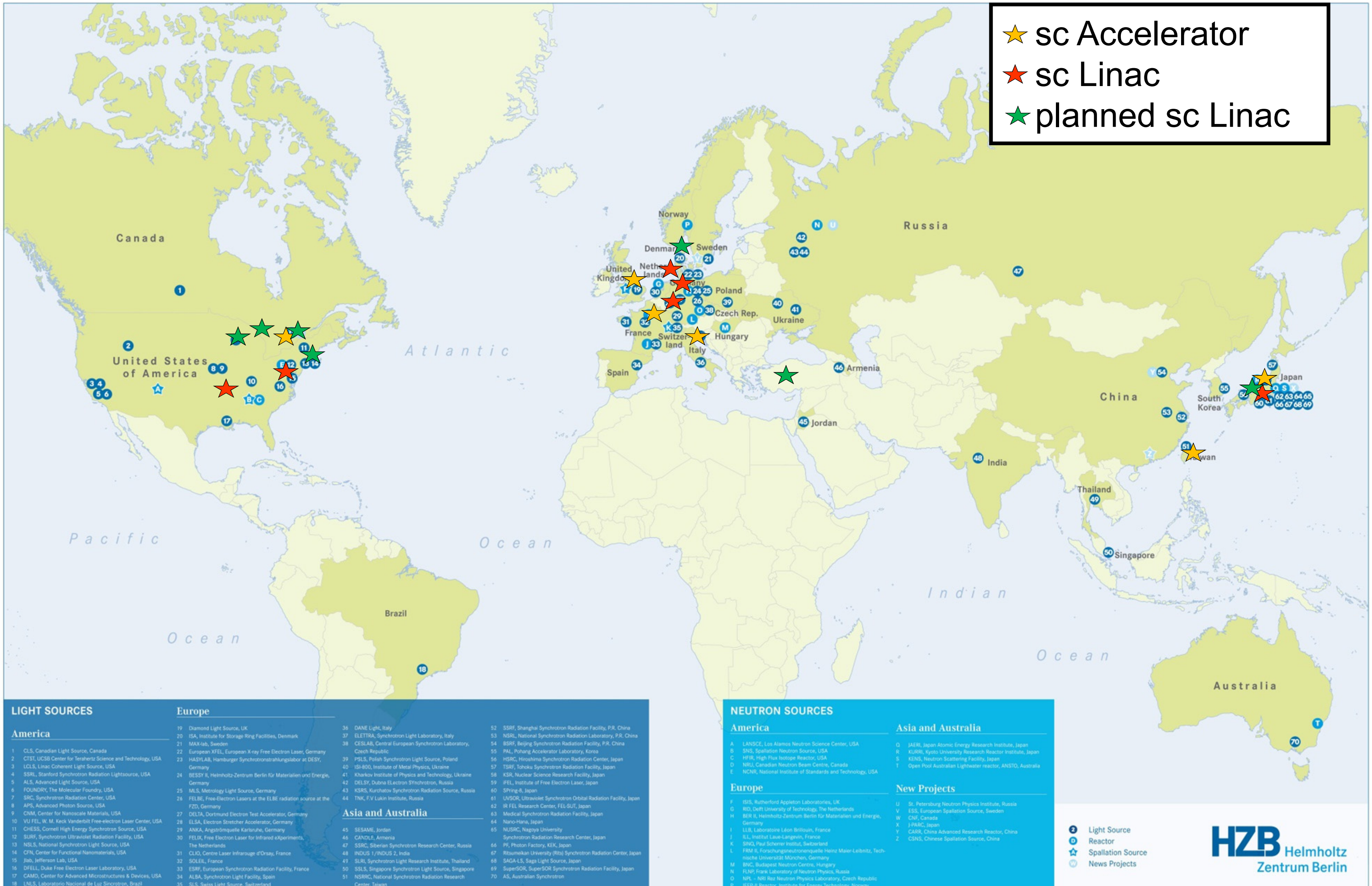
RF Systems for superconducting Linacs

W. Anders, HZB, PAC 11, New York

Worldmap of Accelerators

HZB Helmholtz Zentrum Berlin

WORLDMAP OF LIGHT SOURCES AND NEUTRON SOURCES FOR RESEARCH



Outline

HZB Helmholtz Zentrum Berlin

- Introduction
- SRF linac types, requirements and challenges
- High power RF system architecture
- Klystron vs IOT vs solid state amplifier
- New developments

- RF systems at specific projects (realized and future)
    - Proton Accelerators and Spallation sources
    - FEL sources
    - ERL sources
- Summary

Classification of sc linacs and special requirements

	SC Linac				
	protons		electrons		
Application	spallation source	nuclear physics & driver linac	FEL light source	ERL light source	ERL cooler ring
cw /pulsed Frequency band	pulsed UHF	cw UHF-band	pulsed / cw L-band	cw L-band	cw UHF-band
Beam current: Low: < 100 µA Medium: < 10 mA High: > 10 mA	medium	medium/ high	**Low** avg. beam / **medium** in pulse trains	high	high
RF power single transmitter Low: < 50 kW Medium: < 500 kW High: >500 kW	medium / high	high	cw : low Pulsed: high	low / medium	high
Phase stability Amplitude stability	1° 1 %	1° 1 %	0.01…0.1° 0.01…0.1 %	0.01…0.1° 0.01…0.1 %	1° 1 %

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

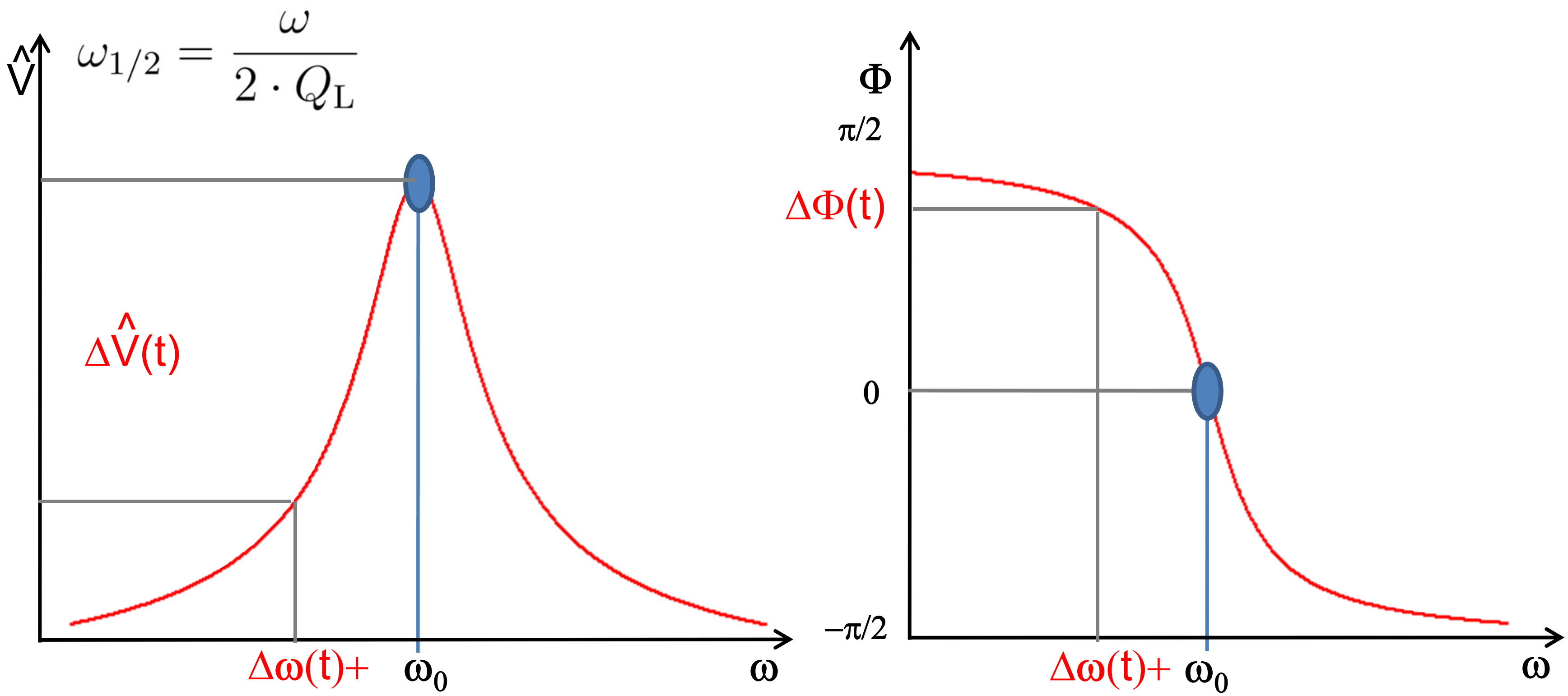
small for sc cavities 1-30 W

+ 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

HZB Helmholtz Zentrum Berlin

P_{RF} = beam loading

energy gain · effective beam current
main contribution to power level at high current accelerators
ERL: >10^{-4} energy recovery eff. ➔ effective current low

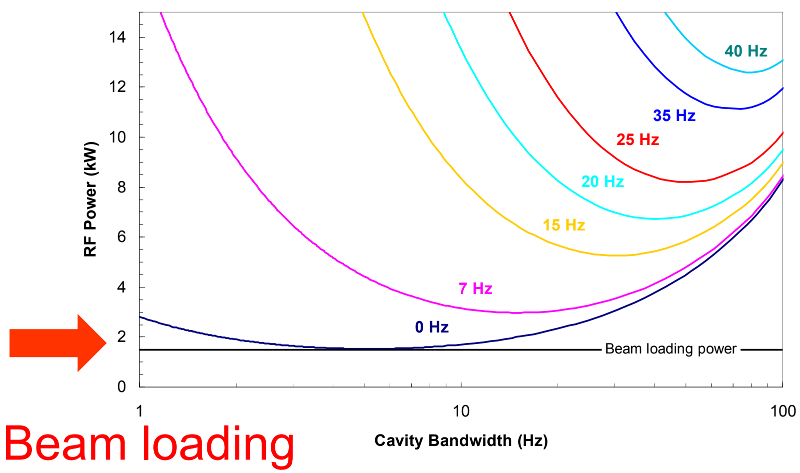
+ cavity losses

small for sc cavities 1-30 W

+ losses in transmission lines

typical 25-30 %

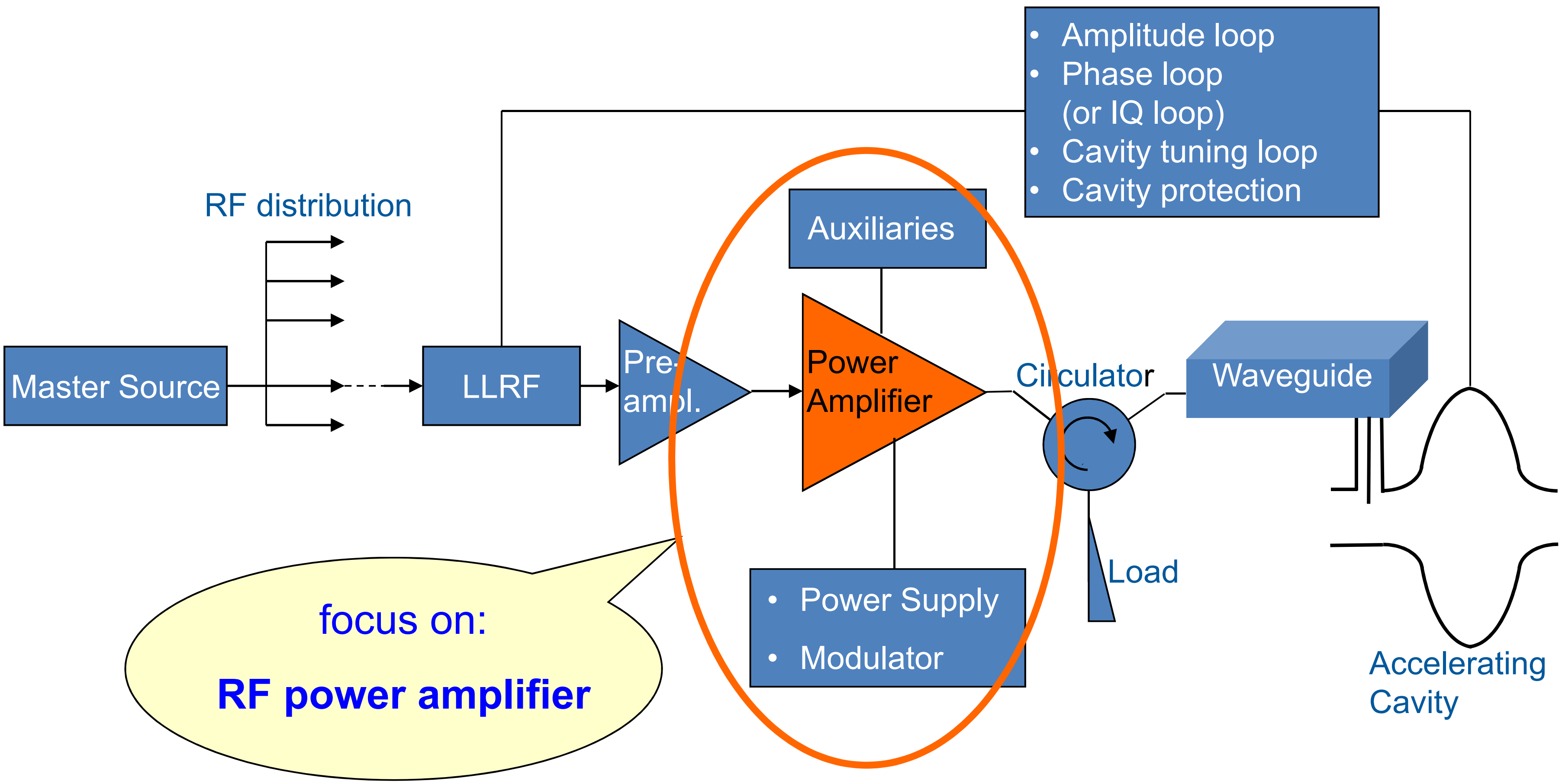
+ headroom for microphonic detuning



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

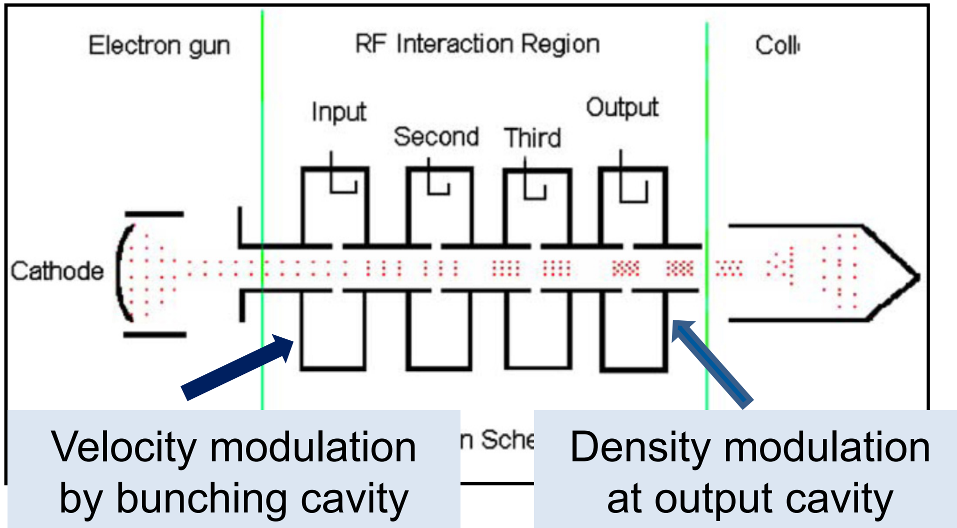
Typical setup of a RF transmitter



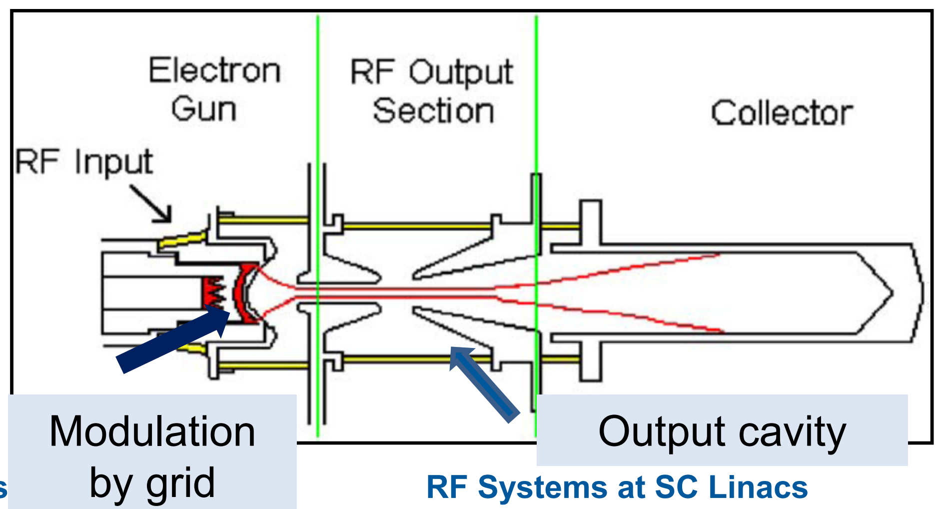
J. Jacob

RF power generation options

Klystron



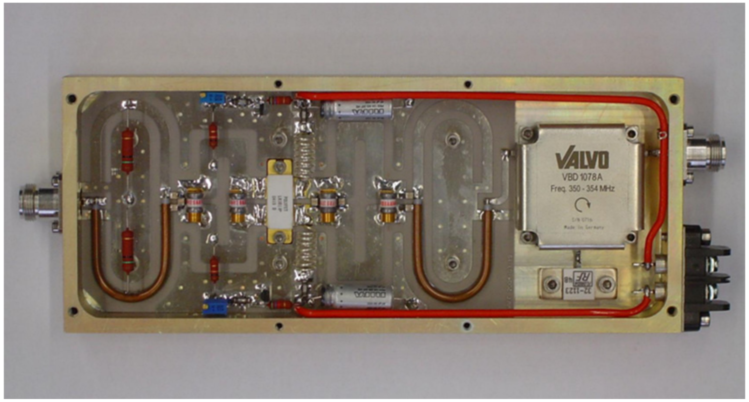
IOT



J. Jacob

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

HZB Helmholtz Zentrum Berlin

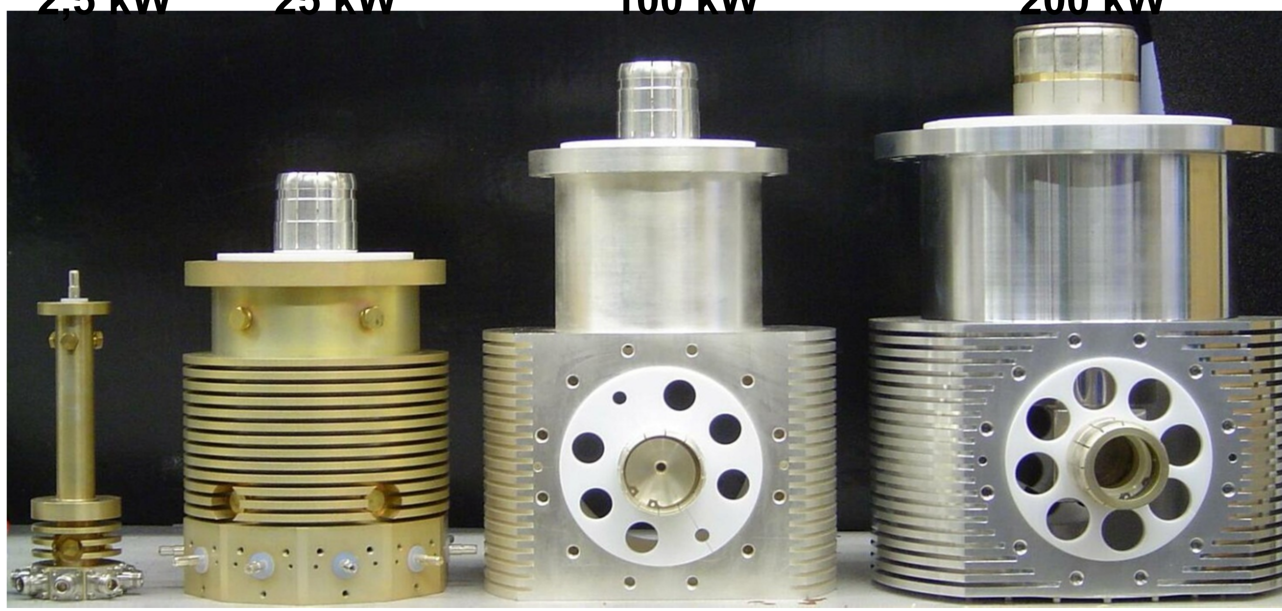


315 W power module

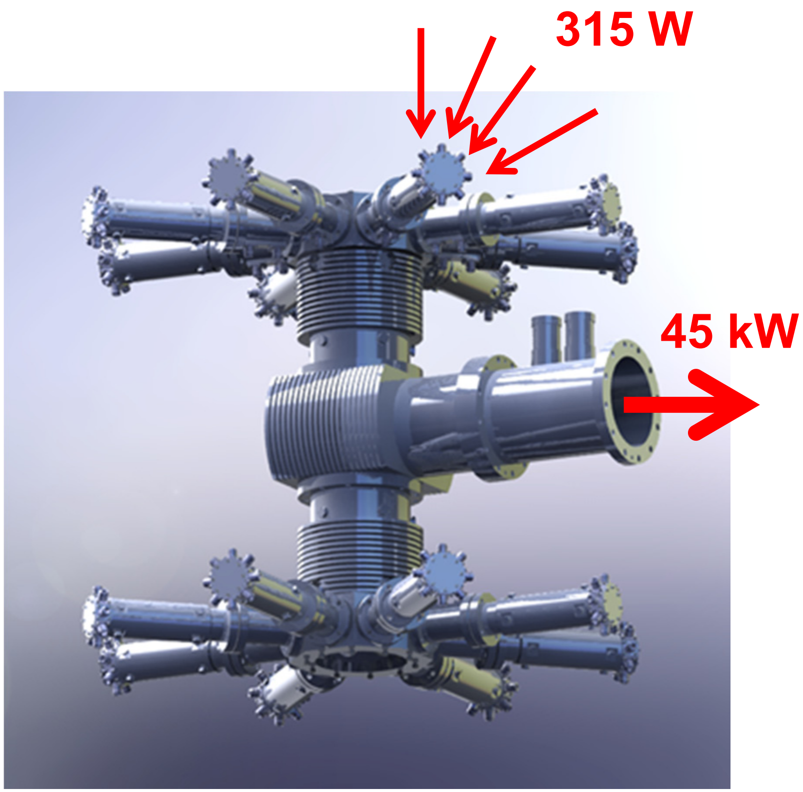
28 V 600 W DC/DC converter

10 x power combiner

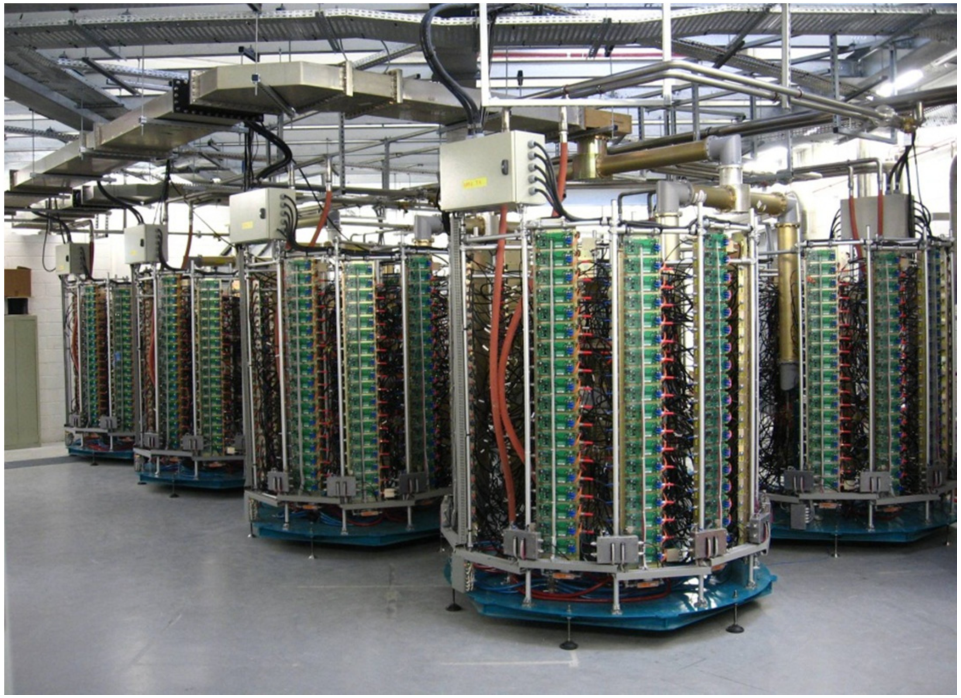
2,5 kW **25 kW** **100 kW** **200 kW**



Ti Ruan



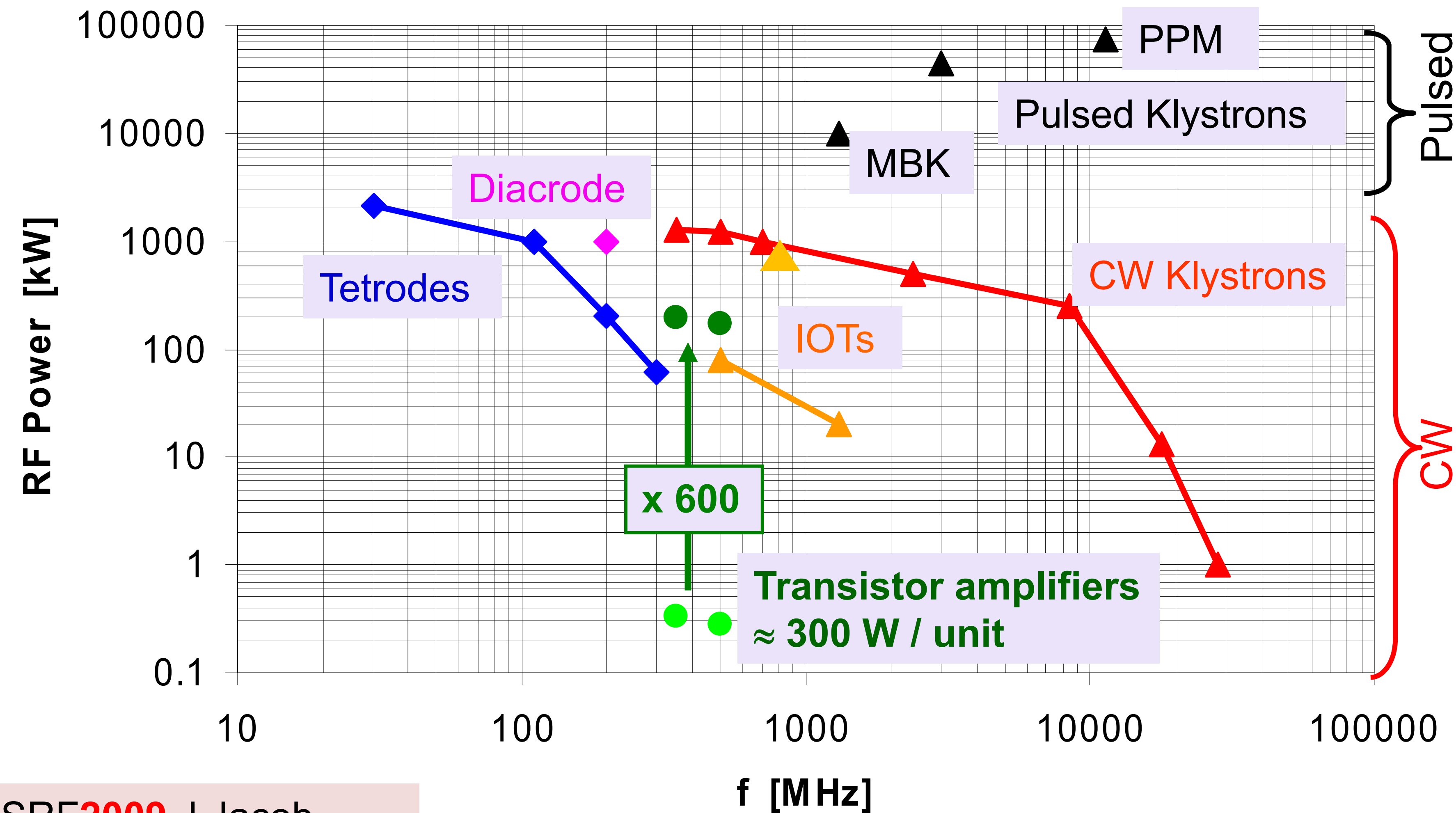
160 way power combiner (AREVA)



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 !!

Power sources -- Status 2009



SRF2009 J.Jacob

IOT– new developments - this conference

Multi beam IOT ➔ higher power levels

ID: 2966 Development of a 402.5 MHz 140 kW Inductive Output Tube (IOT)

Presenter Michael Read (CCR, San Mateo, California)

Authors Michael Read, Thuc Bui, Robert Lawrence Ives, Robert Jackson (CCR, San Mateo, California), Henry Freund (SAIC, McLean)

ID: 2553 350 MHz, 200 kW Mulitple Beam Inductive Output Tube

Presenter Robert Lawrence Ives (CCR, San Mateo, California)

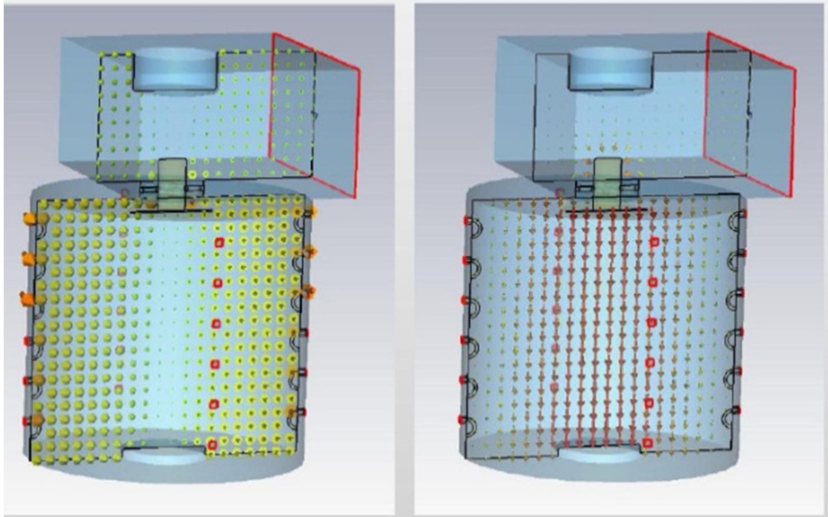
Authors Robert Lawrence Ives, Robert Jackson, David Marsden, Michael Read (CCR, San Mateo, California), Edward Lawrence Eisen, Takuji Kumura (CPI, Palo Alto, California)

Solid state amplifiers go towards higher frequencies

10 kW 1.3 GHz solid state amplifier (Bruker)

HZB Helmholtz Zentrum Berlin

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



H field

Homogenous magnetic coupling of all input loops

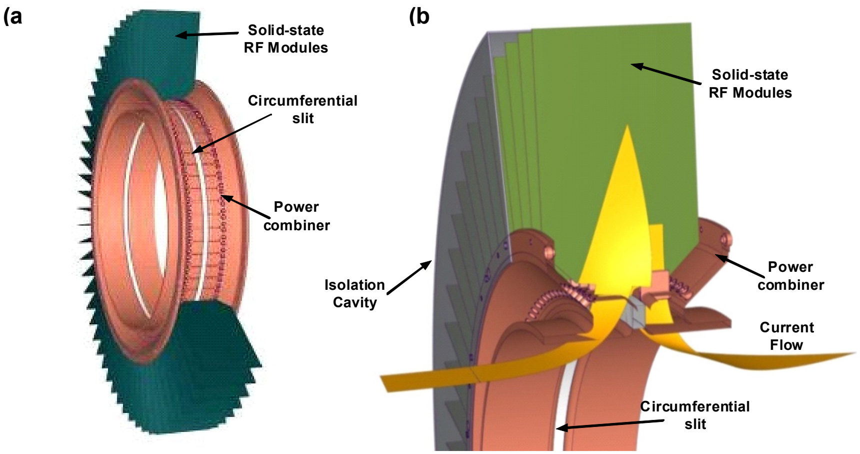
E field

Strong capacitive coupling to the output waveguide

Solid State Amplifiers – new developments (III)

Radiation resistant solid state amplifier, direct attached to nc cavity proposed for spallation source

20kW RF power module – SiC solid state



Direct drive RF modules (O.Heid Siemens)

ID: 2704 Solid State RF Power - The route to 1W per Euro Cent?

Speaker Oliver Heid (Siemens AG, Erlangen)

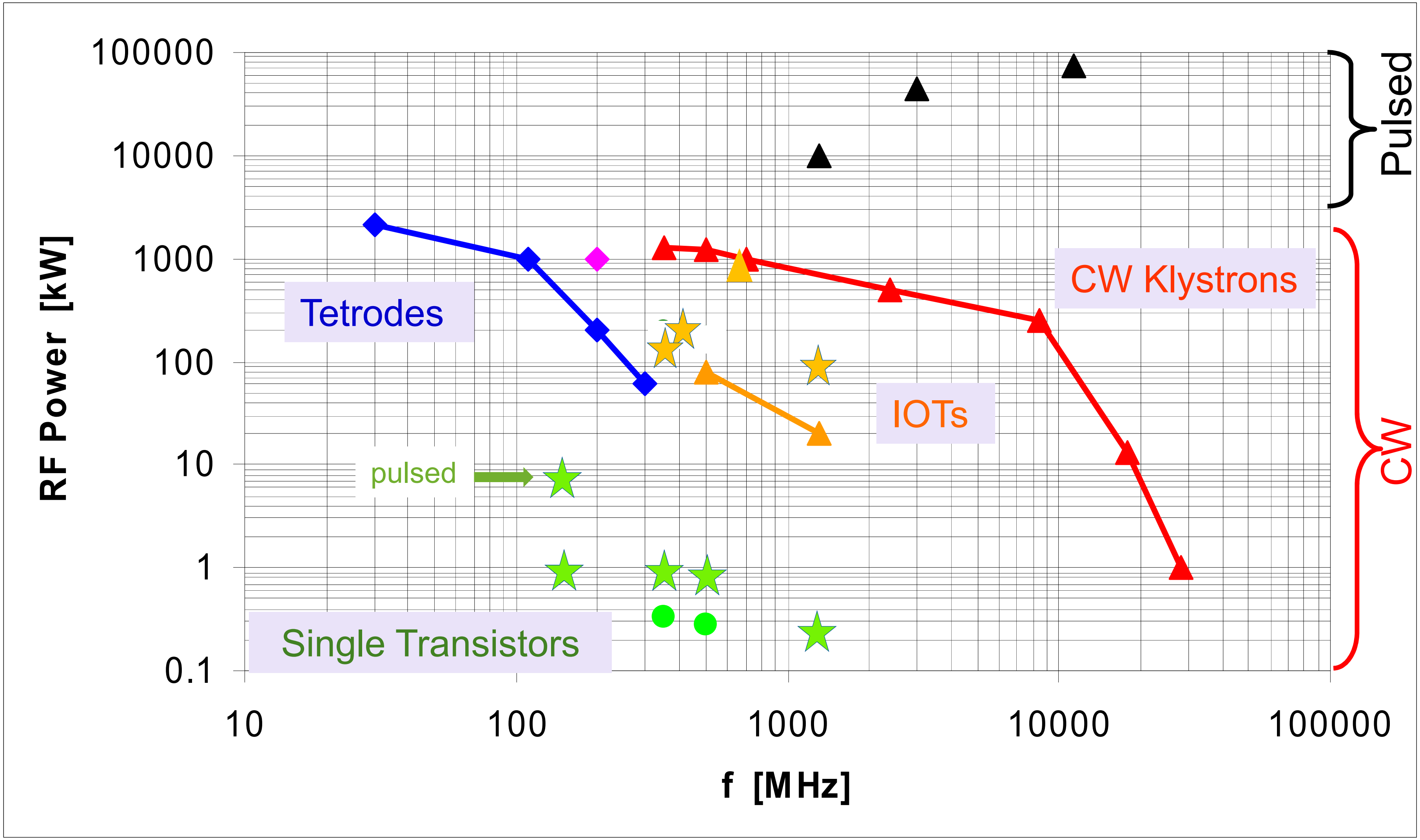
Authors Oliver Heid, Timothy Hughes (Siemens AG, Erlangen)

ID: 2706 Solid State Direct Drive RF LINAC: High Power Experimental Program

Presenter Timothy Hughes (Siemens AG, Erlangen)

Authors Timothy Hughes, Oliver Heid (Siemens AG, Erlangen)

Power sources 2009 → 2011



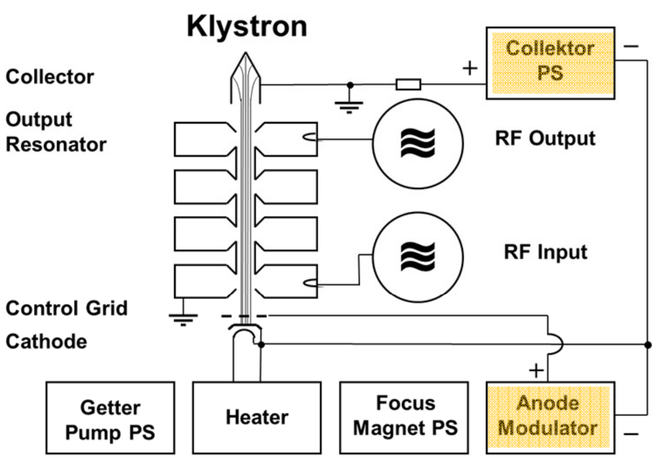
Klystron vs IOT vs solid state amplifier

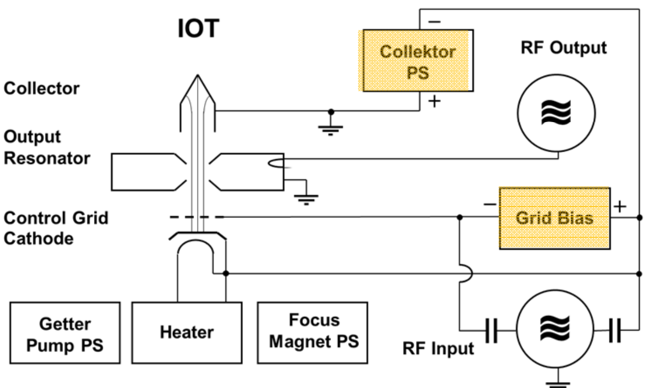
HZB Helmholtz Zentrum Berlin

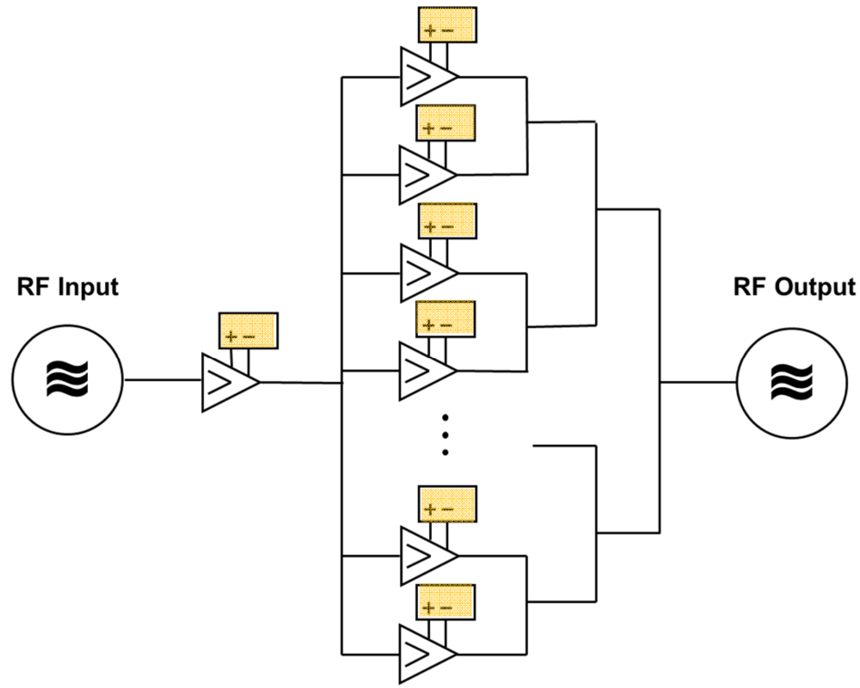
	Klystron	IOT	Solid state
Power level	Up to MW	< 100 kW but R&D for higher level ongoing	200 W-1 kW single transistor, sum it up
Efficiency	High efficiency in saturation, which drops rapidly at reduced power Class A operation	High efficiency, which does not drop quickly at reduced power. Class B operation	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

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

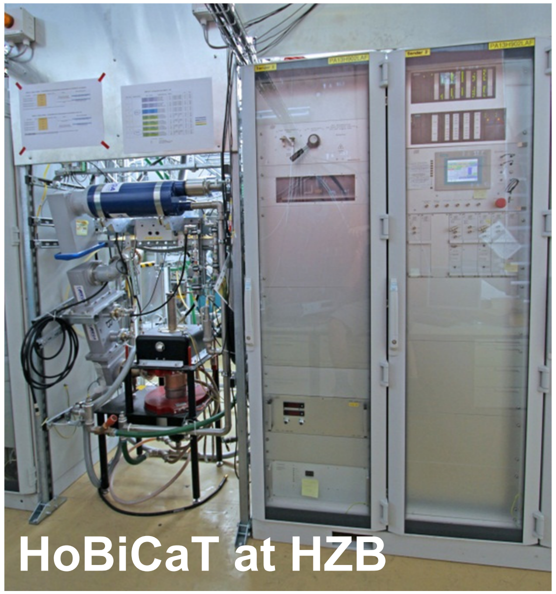
Careful specification of main power supplies is essential







Low noise transmitters at HZB



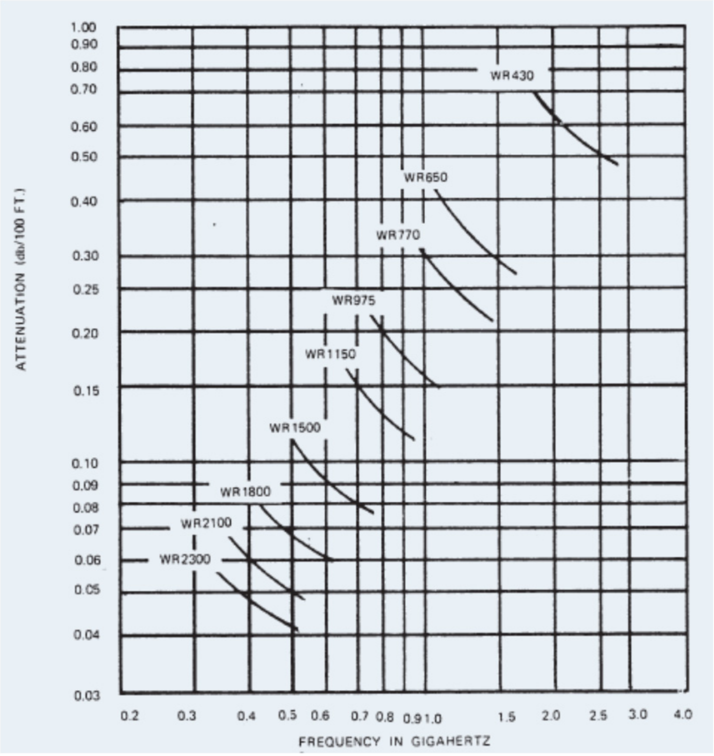
IOT 16 (25) kW_{cw} 1.3 GHz
Anode PS:
31 kV 1,3 A Stability < 1 * 10^{-4}_{pp}
Bias PS:
150 V ± 300 mA < 2 * 10^{-4}_{pp}

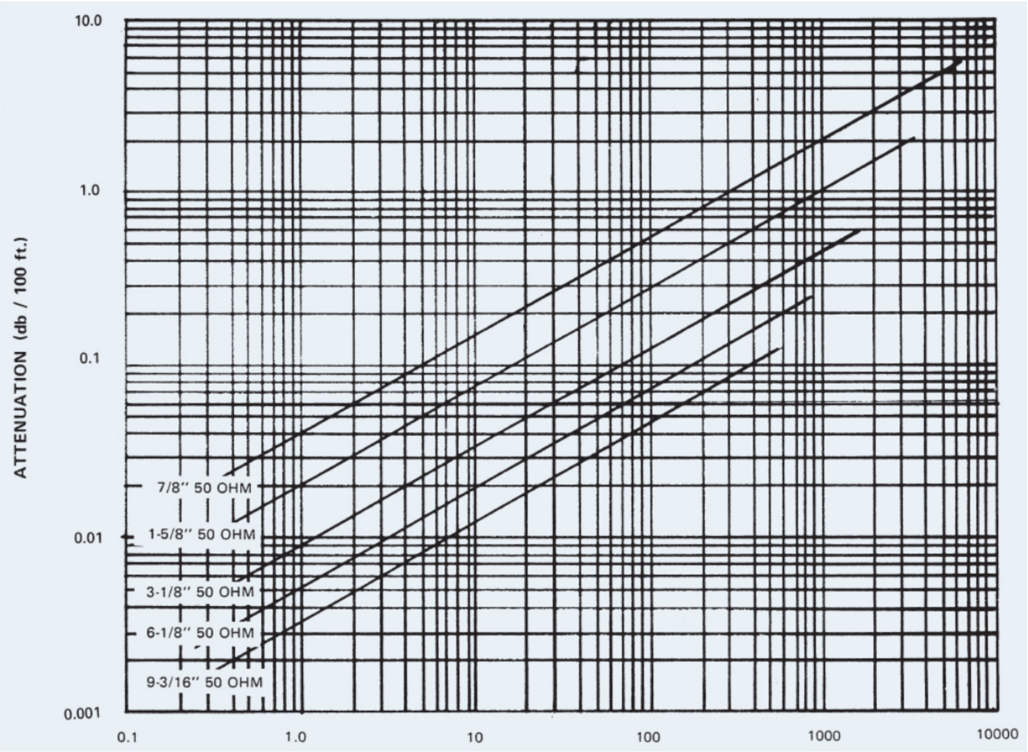
➔ RF amplitude noise: < 2 * 10^{-4}_{pp}
➔ RF phase noise: < $0.1°_{pp}$

0.008° with closed loop

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





***VHF to UHF frequencies*:**

Coaxial transmission lines, losses increase as √f

***UHF and higher*:**

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

Spallation source – FEL – ERL

- operating
- in installation phase
- planned

Projects: SNS

Host: ORNL (Oak Ridge National Laboratory)
Application: spallation source

Frequencies: 805 MHz
Transmitter power: 14 x **550 kW klystron** (only sc linac)
Pulsed 60 Hz 6.6 (8)% duty cycle
Stability: 0.5° phase   0.5% amplitude

Project status: operating

Klystron gallery 550 kW 805 MHz

(T. Hardeck)

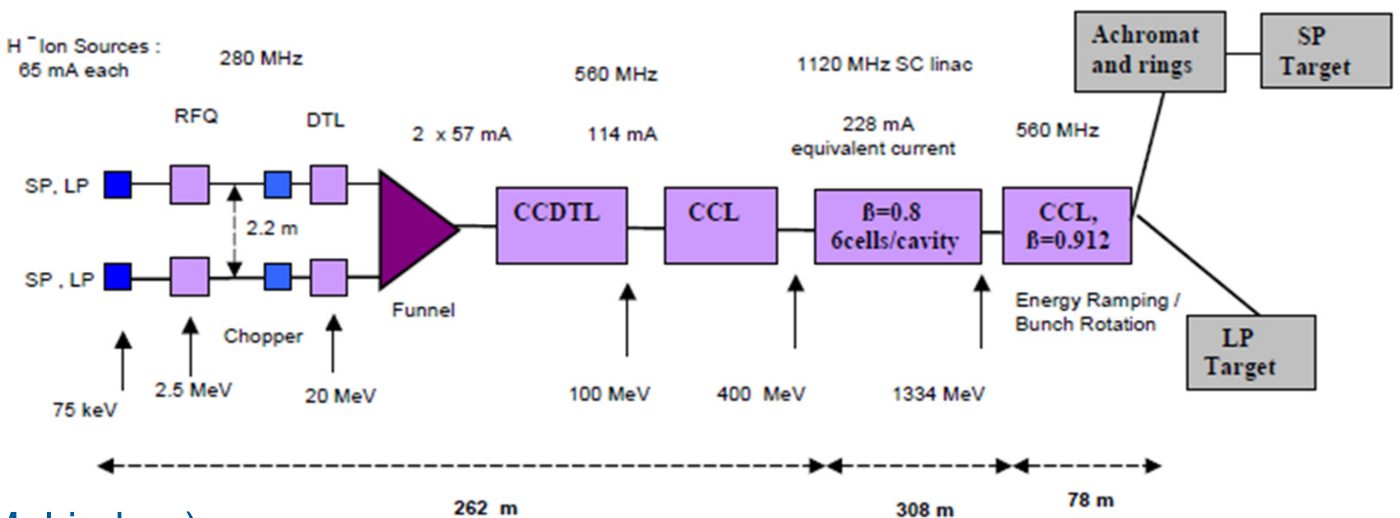
Projects: ESS

Location: Lund (Sweden)
Application: spallation source

Frequencies: 352 / 704 MHz
Transmitter power: **350 kW / 1.2 MW klystron**
Number of transmitters: 45
Pulsed 20 Hz 4% duty cycle
Stability: 1° phase 1% amplitude

Project status: predesign phase

Candidate for direct drive solid state???



(D.Romuald, M. Lindros)

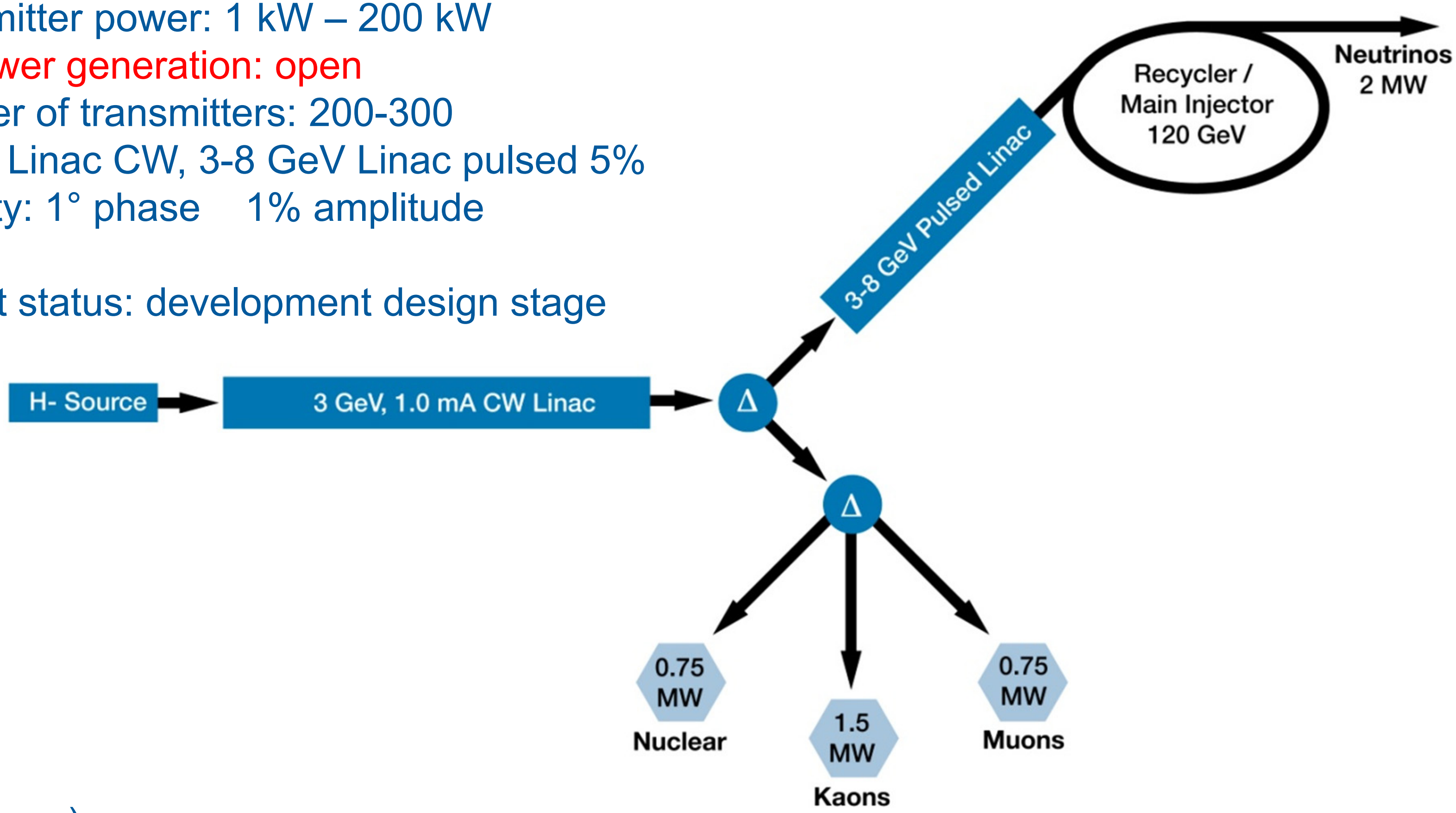
Projects: Project X

Solid state / klystron???

Host: FermiLab (Chicago)
Application: Particle Physics

Frequencies: 162.5 / 325 / 650 / 1300 MHz
Transmitter power: 1 kW – 200 kW
RF power generation: open
Number of transmitters: 200-300
3 GeV Linac CW, 3-8 GeV Linac pulsed 5%
Stability: 1° phase 1% amplitude

Project status: development design stage



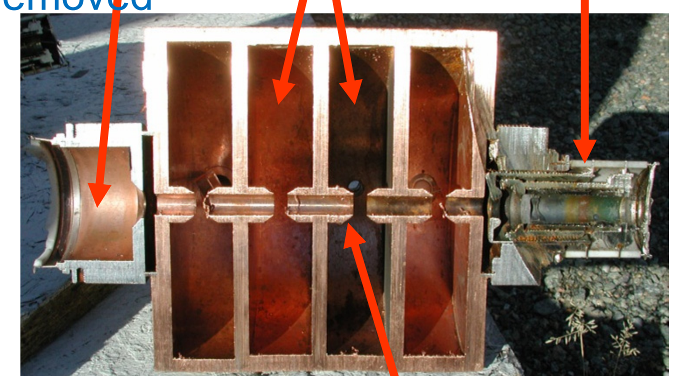
(C. Ginsburg)

Projects: CEBAF

Host: JLAB (Newport News)
Application:
Frequencies: 1500 MHz
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
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)

Projects: Flash / XFEL

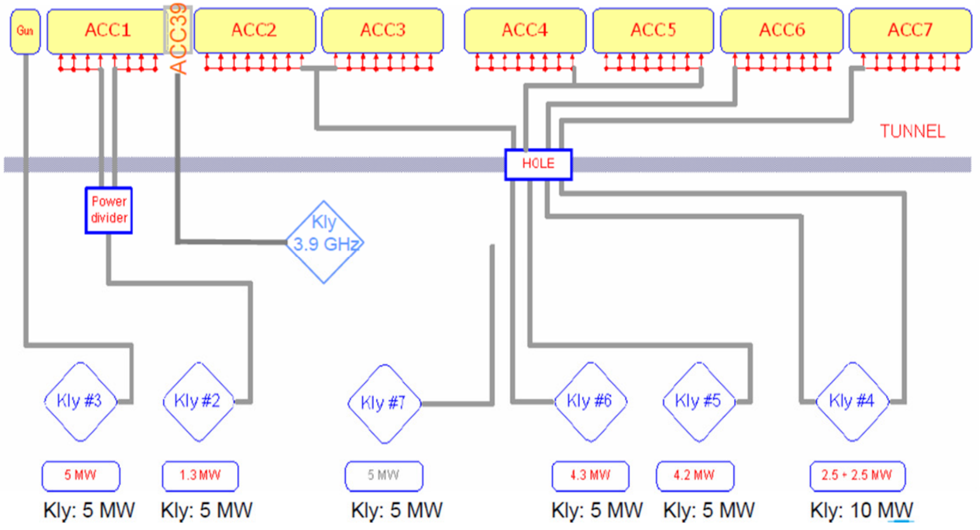
HZB Helmholtz Zentrum Berlin

Host: DESY (Hamburg)
Application: FEL light source

Frequencies: 1300 MHz
Transmitter power: FLASH: 4 x 5 MW+ 1x 10 MW_{pulsed} klystron
1 x 80 kW 3.9 GHz Klystron
XFEL: 27 x 10 MW_{pulsed} Multi beam klystron
1 x 80 kW 3.9 GHz Klystron
Stability: 0.01° phase 0.01% amplitude
Project status: FLASH operating, XFEL construction phase

Multi beam klystron: Thales/CPI/Toshiba

10 MW pulsed transmitter



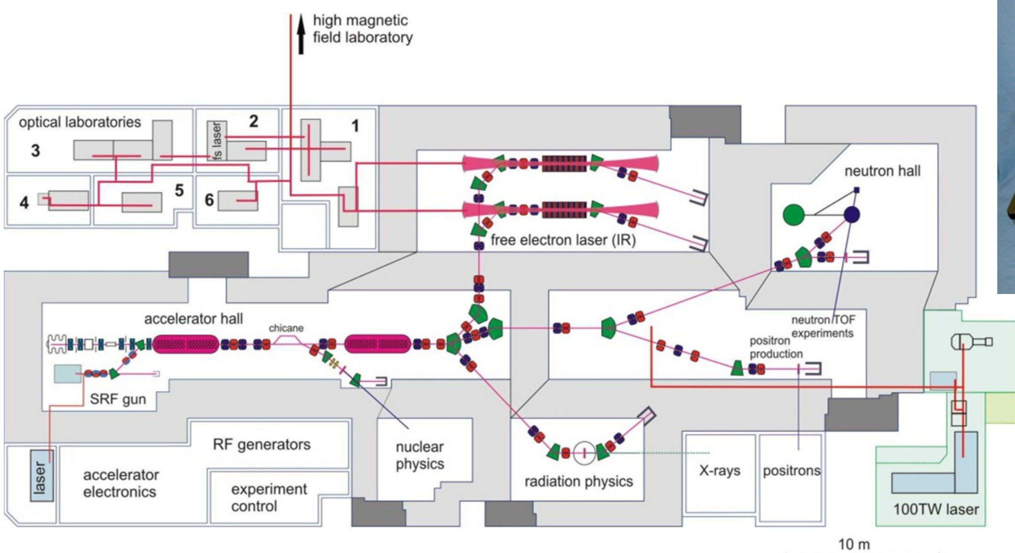
RF system at FLASH (S. Choroba)

Projects: ELBE

Host: HZDR (Helmholtz Zentrum Dresden Rossendorf)
Application: Infrared FEL

Frequencies: 1300 MHz
Transmitter power: 2 x 10 kW Klystron
upgrade to → 8 x 10 kW solid state
Stability: 0.1° phase 0.02 % amplitude

Project status: operating, now upgrade



Layout of ELBE

(H. Büttig)

10 kW 1.3 GHz klystron

10 kW 1.3 GHz solid state transmitter (Bruker)

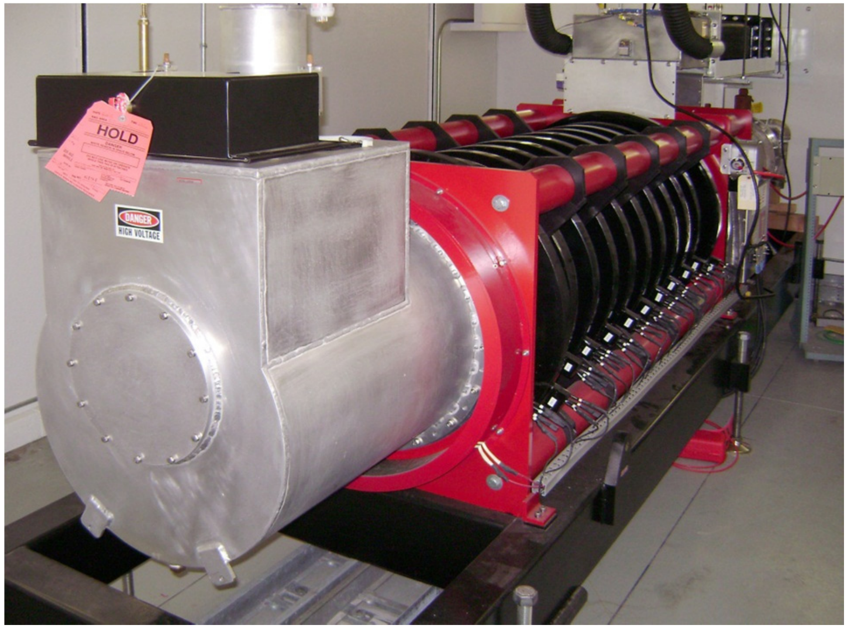
Projects: BNL ERL

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

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

Project status: in installation

50 kW IOT transmitter



1 MW klystron

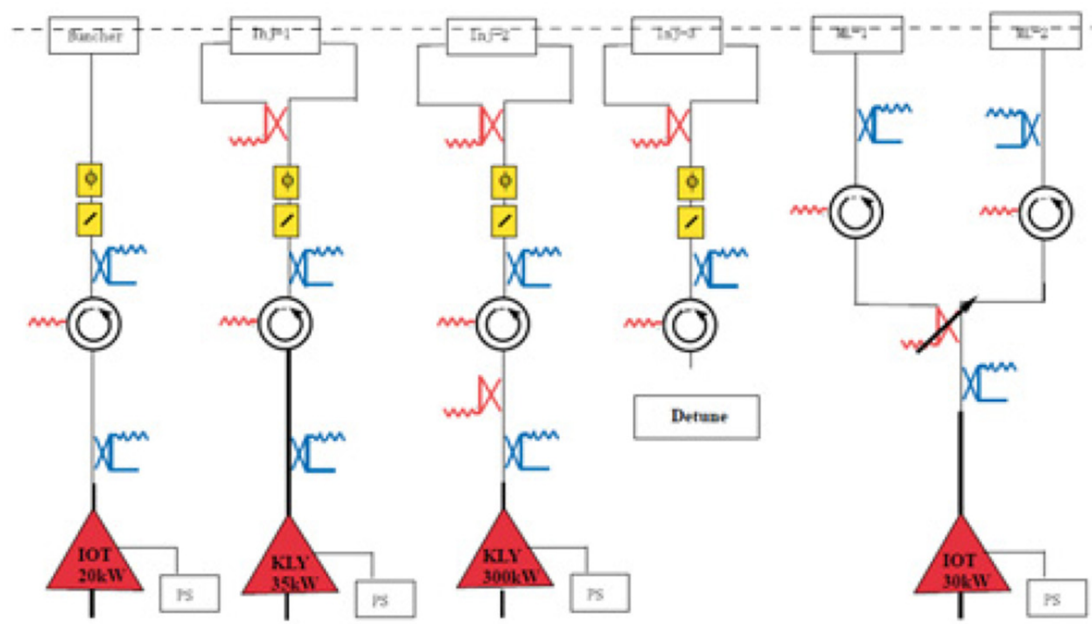
(S. Belomestnykh)

Projects: cERL

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

Frequencies: 1300 MHz
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



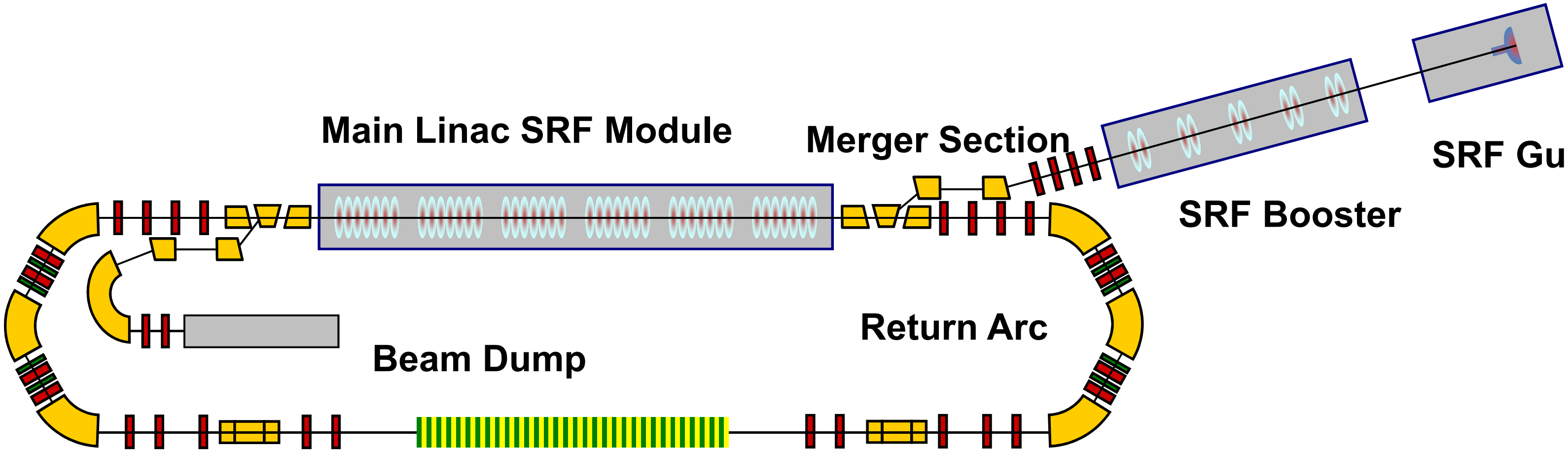
(S. Fukuda, IPAC 2010)

Projects: BERLinPro

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

Frequency: 1300 MHz
Transmitter power: 6 x **10 kW_{cw}** **solid state** for linac
3 x **300 kW_{cw}** **klystron** for booster and gun
Stability: 0.1° phase 0.1% amplitude

Project status: construction phase 2011-2015

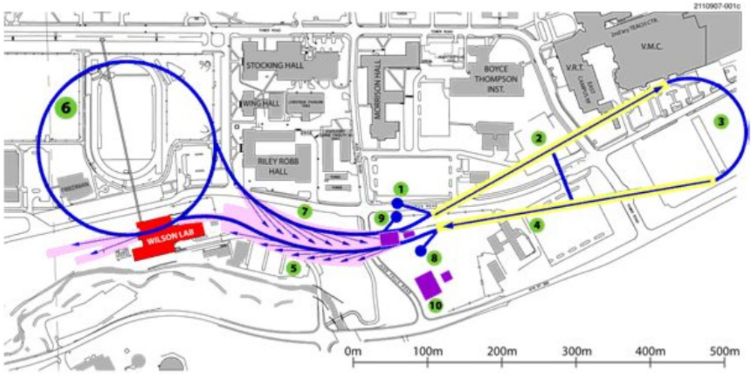


Projects: Cornell ERL

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

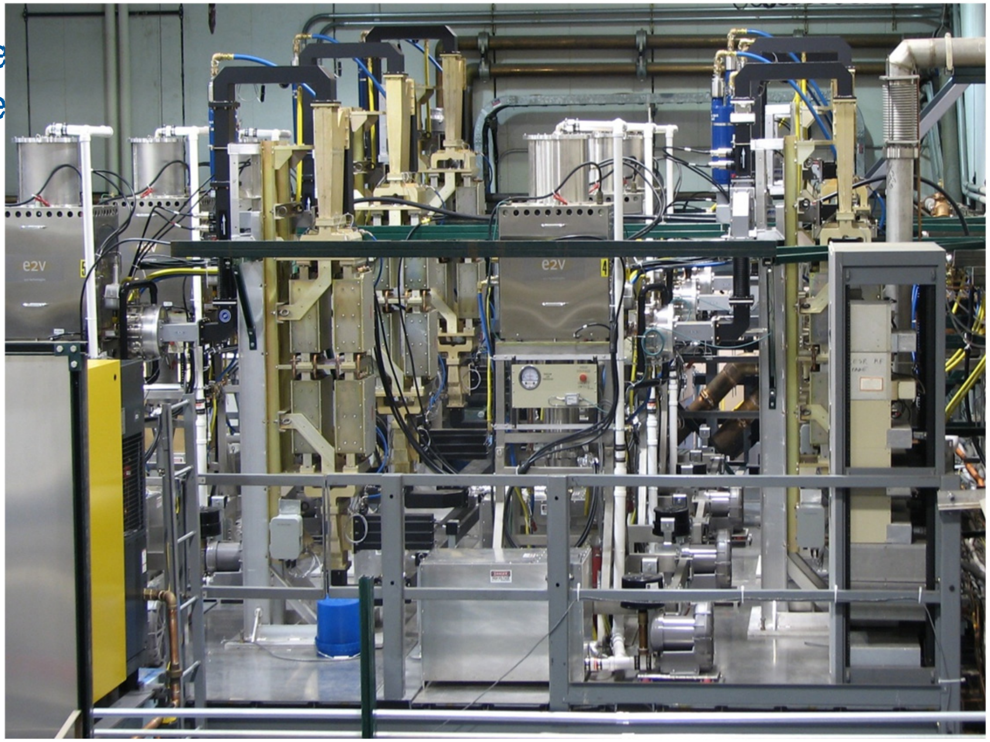
Frequencies: 1300 MHz
Transmitter power: 5 x 135 kW_{cw} klystron operating at injector
12 x 135 kW_{cw} klystron planned
384 x 5 kW_{cw} planned
Stability: (inj) 0.1° phase 0.1% amplitude
linac: 0.05° phase 0.01% amplitude

Project status: injector operating,
Cornell ERL planned



Expanding CESR to the Cornell ERL

(S. Belomestnykh)



5 x 135 kW 1.3 GHz klystron transmitter

Summary

HZB Helmholtz Zentrum Berlin

	SC Linac				
	protons		electrons		
Application	spallation source	nuclear physics & driver linac	FEL light source	ERL light source	ERL cooler ring
cw /pulsed Frequency band	pulsed UHF	cw UHF-band	pulsed / cw L-band	cw L-band	cw UHF-band
Beam current: Low: < 100 µA Medium: < 10 mA High: > 10 mA	medium	medium/ high	**Low** avg. beam / **medium** in pulse trains	high	high
RF power single transmitter Low: < 50 kW Medium: < 500 kW High: >500 kW	medium / high	high	cw : low Pulsed: high	low / medium	high
Phase stability Amplitude stability	1° 1 %	1° 1 %	0.01…0.1° 0.01…0.1 %	0.01…0.1° 0.01…0.1 %	1° 1 %
	klystron	klystron	klystron / solid state	klystron / IOT / solid state	klystron / IOT

Summary

HZB Helmholtz Zentrum Berlin

- SRF linacs are used for a variety of scientific applications from nuclear physics to radio isotopes production to light source facilities
- High-β linacs operate mostly in L band. Proton and ampere class electron linacs use UHF band RF systems.
- Typical setup of a transmitter are discussed.
- RF power sources were presented. IOT compete sucessfully in the medium power level with klystron technology. Solid state amplifiers are rapidly becoming the technology of choice at UHF frequencies at medium power transmitters. New transistors rapidly increase in power level as well as in frequency.
- Examples of operating and planned RF systems are shown.

Acknowledgement

I would like to thank people who provided information, slides and pictures for this talk:

S. Belomestnykh (BNL)
J. Jacob (ESRF)
Ti Ruan (Soleil)
D. Romuald (CEA)
M. Lindros (ESS)
T. Hardeck (SNS)
C. Ginsburg (Project X)
S. Choroba (DESY)
T. Powers (CEBAF)
H. Büttig (ELBE)