RF systems for CW SRF linacs

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LINAC08
September 29 – October 3, 2008

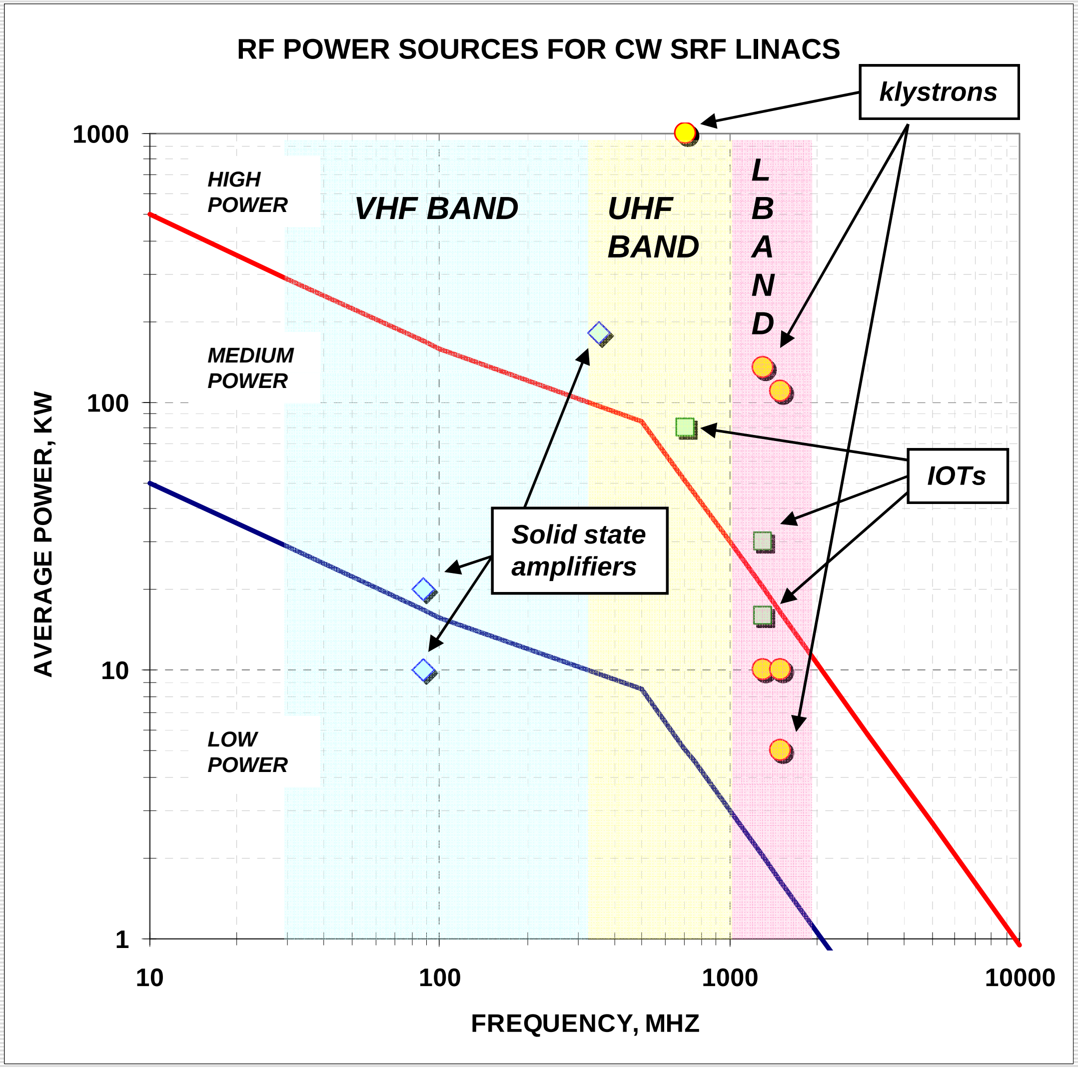
Outline

- ❑ Introduction: CW SRF linac types, requirements and challenges
- ❑ High power RF system architecture
- ❑ RF power generation options: klystron vs IOT vs solid state amplifier
- ❑ Specific projects, operating or under construction:
  - *L band*
    - ❑ JLab FEL & CEBAF
    - ❑ ELBE
    - ❑ ALICE
    - ❑ Cornell ERL injector
  - *UHF band*
    - ❑ ERL prototype for electron cooling and eRHIC at BNL
  - *VHF band*
    - ❑ SPIRAL-2
- ❑ Future projects and requirements
- ❑ Summary

Introduction

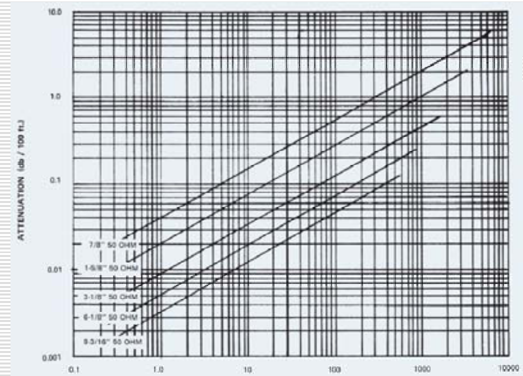
- One can distinguish four types of CW SRF linacs:
  - Low-current high-β linacs: typically L band, low to medium RF power
  - ERLs: L or UHF band, low to medium RF power
  - High-current high-β injectors/drivers: L or UHF band, medium to high RF power
  - Low-β linacs: VHF band, low o medium RF power
- Requirements/challenges:
  - Provide stable, reliable source of RF power
  - Maintain stable cavity field (amplitude and phase) - LLRF
  - High efficiency of converting AC power to RF and transferring it to SRF cavities
  - High availability of the RF system
  - Easy maintainability
  - Cost-effective design
  - Compactness, especially for large installations (e.g. CEBAF)
- In this talk we will consider only medium and high RF power systems

High/medium/low RF power



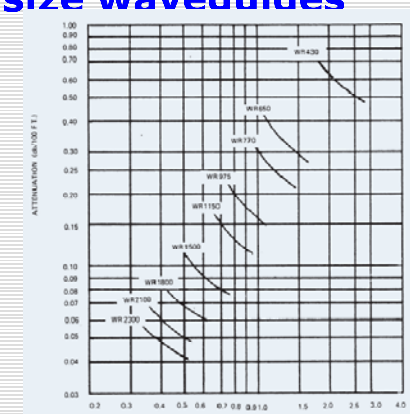
***VHF to UHF frequencies*:**

Coaxial transmission lines, losses increase as √f



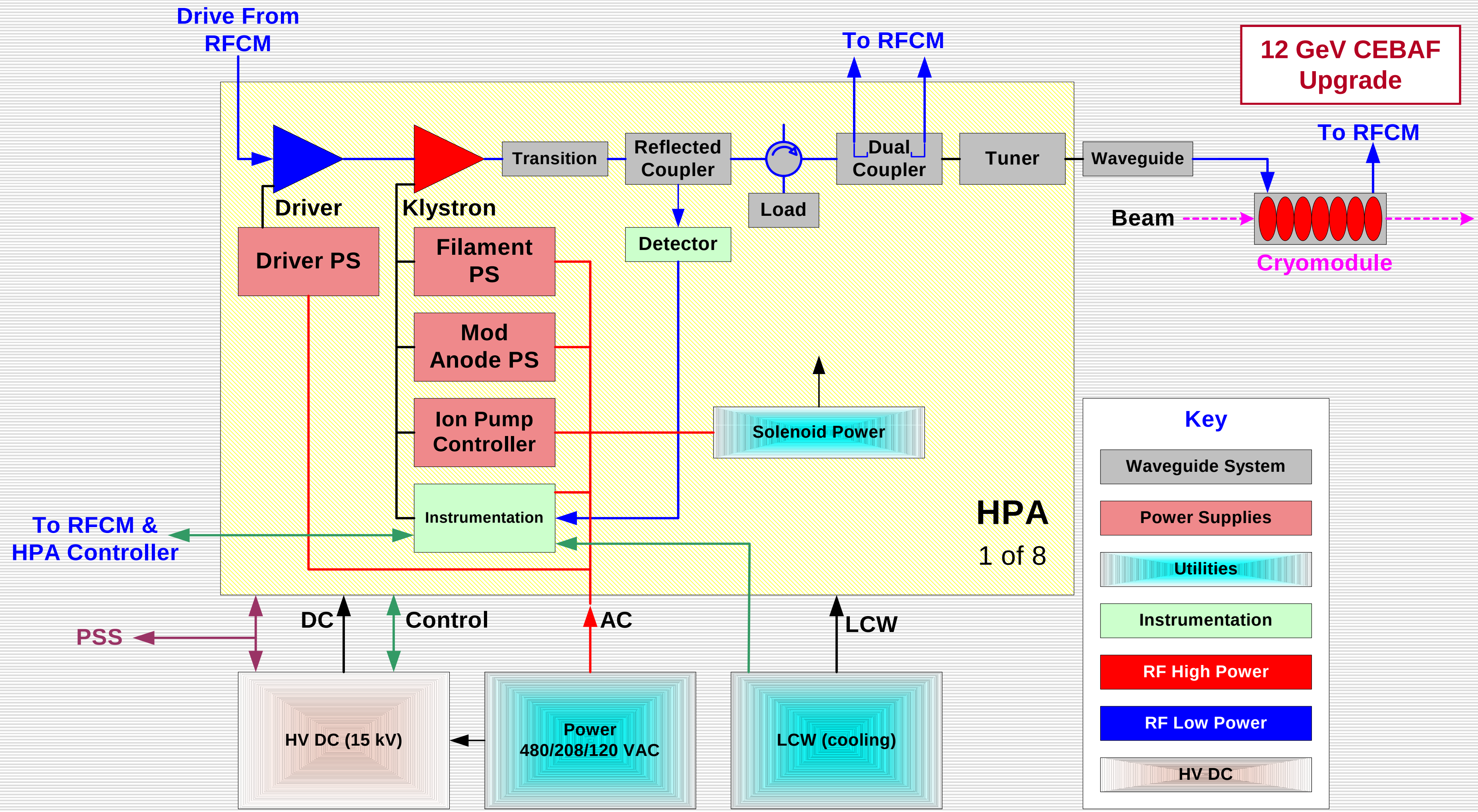
***UHF and higher*:**

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



CW SRF system architecture

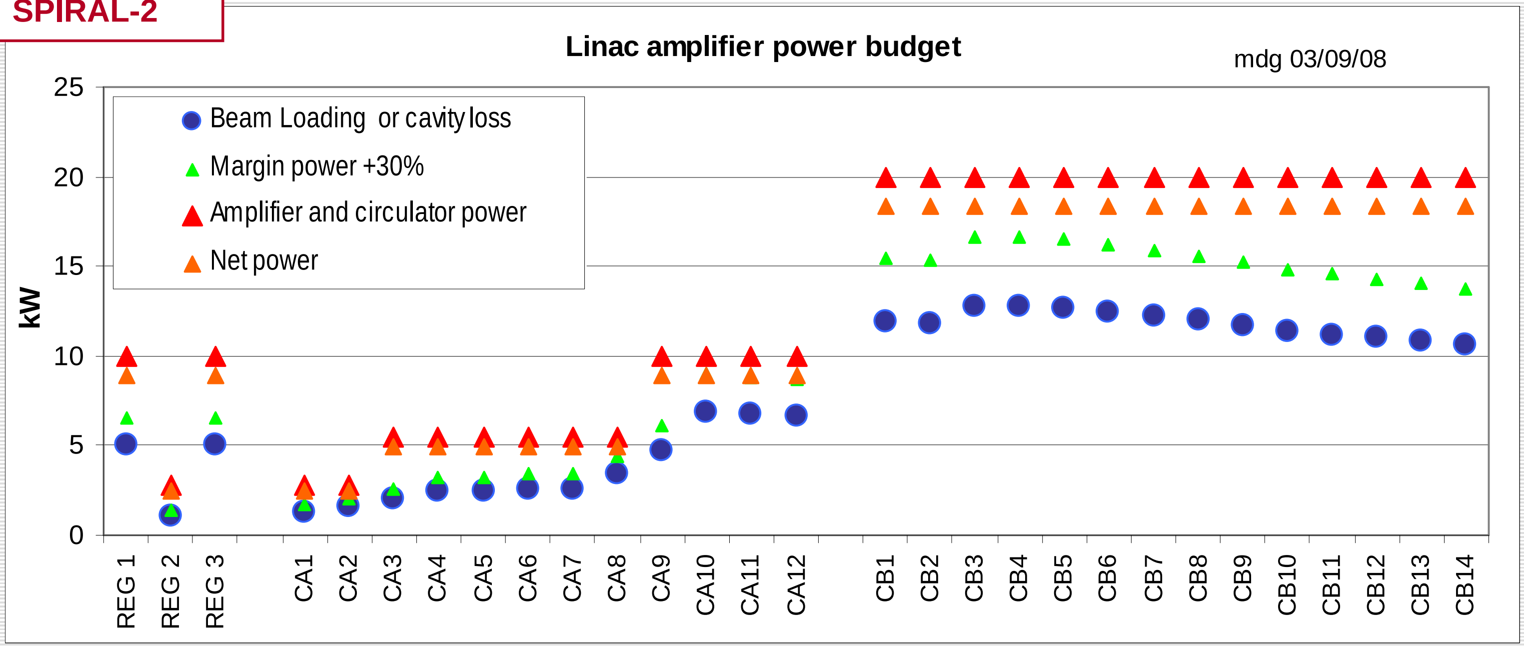
All CW SRF linacs use a simple architecture with one RF high power amplifier per cavity. Reasons: flexibility, available RF power sources, requirements to fiels stability, efficiency of RF system, …



How RF power spec is set?

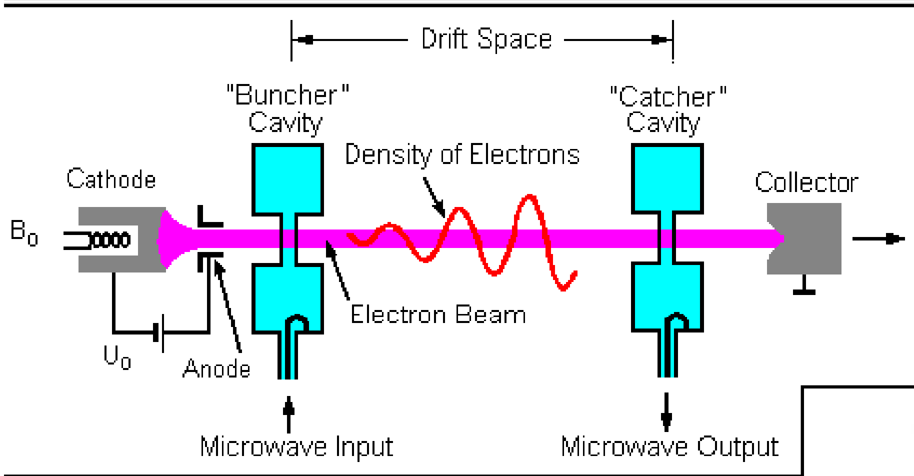
1. Calculate beam loading
2. Add margin for regulation
3. Set requirement for RF power available at the cryomodule for each family of cavities
4. Set requirement for power available at the high power amplifier taking into account losses in the transmission line elements

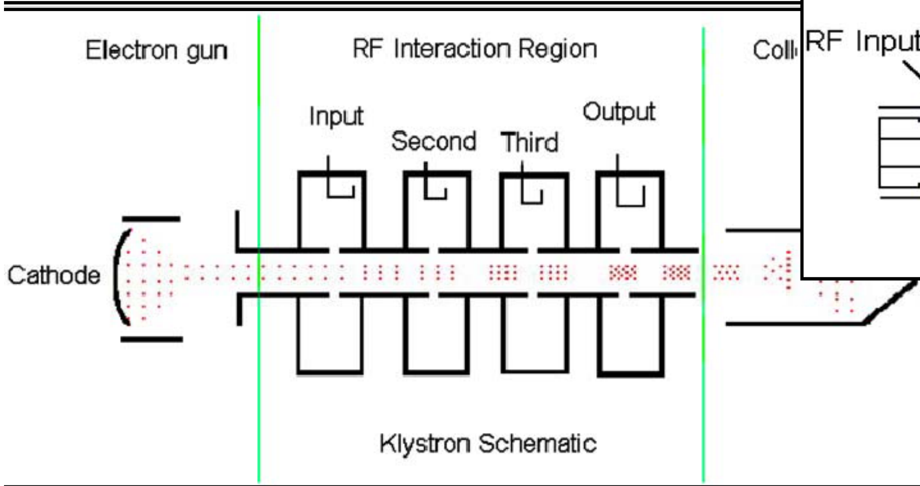
SPIRAL-2



RF power generation options

Klystron

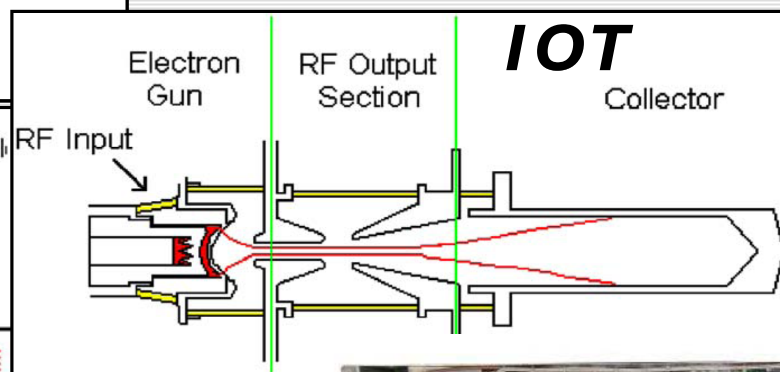


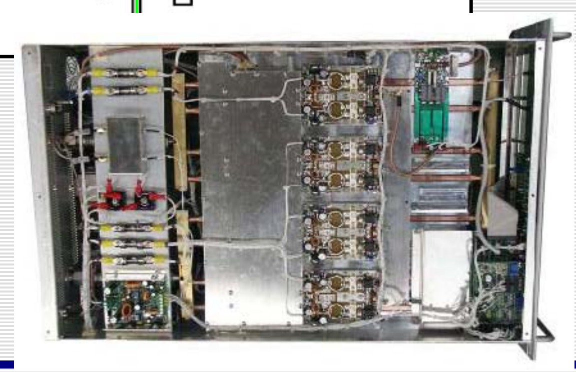


RF power generation at higher frequencies is still dominated by vacuum tubes: klystrons and, with the success in broadcast applications, IOTs

At lower frequencies tetrodes were traditionally used, but recent progress in solid state technology will make it the technology of choice in VHF and UHF bands, except when very high power is required.

IOT

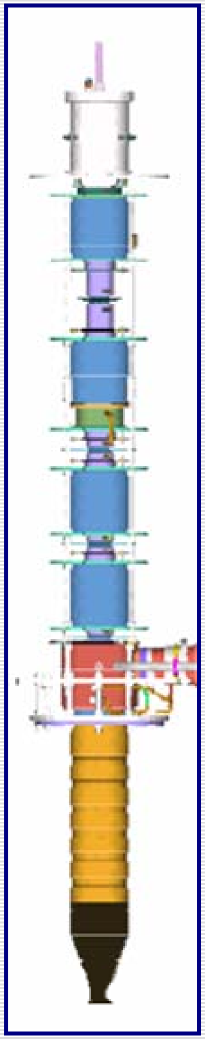




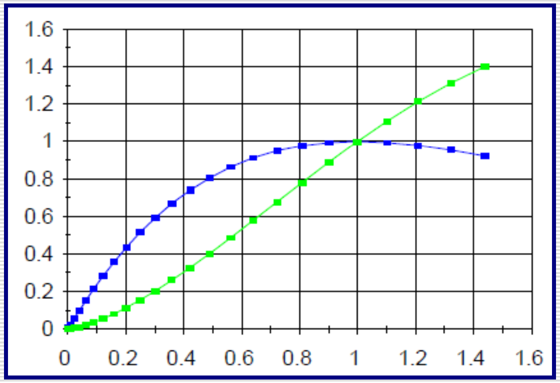
Solid state

RF power generation options

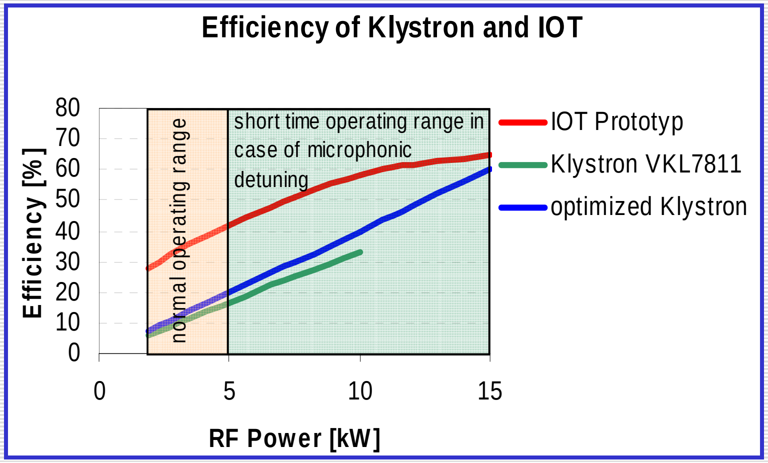
Choice of RF power source: klystron vs. IOT



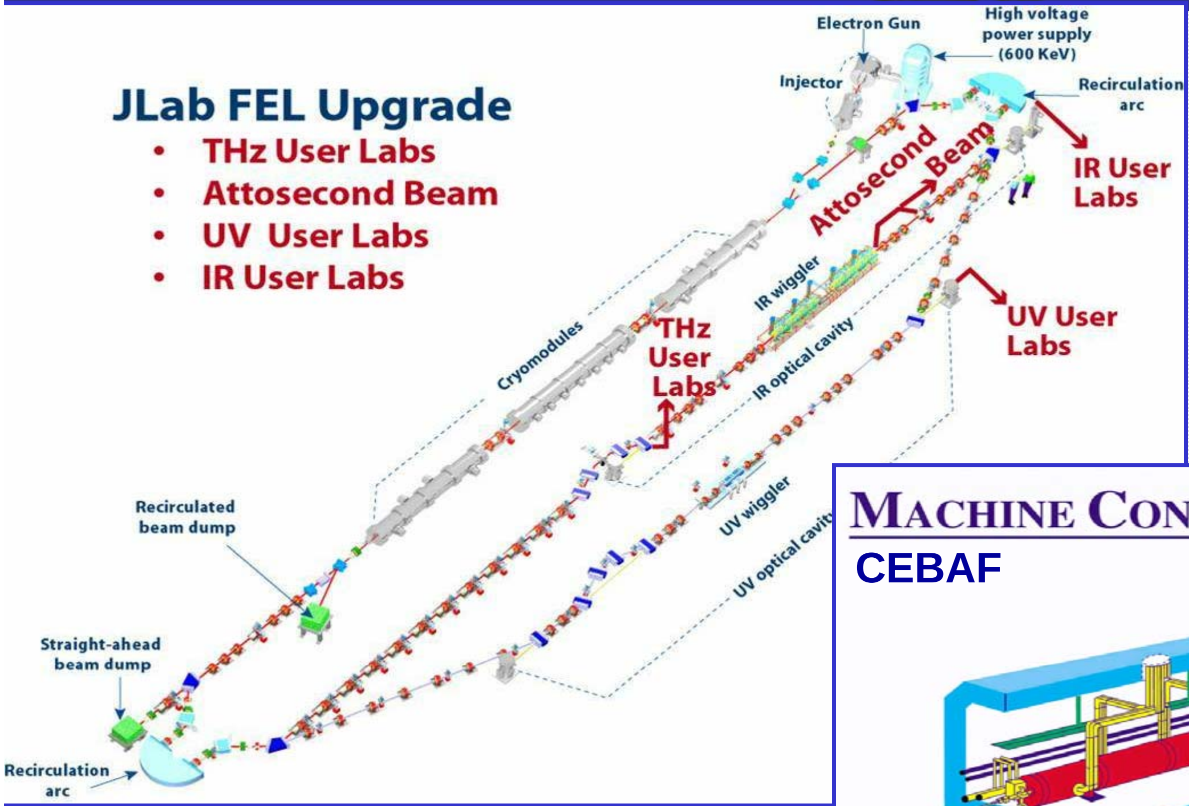
Injector	Main linac
Klystron	IOT
Electron bunches are formed by velocity modulation from the cavities translated into density modulation in the drift spaces	Density modulation directly from cathode
Several bunching cavities, optional mod anode	Control grid
High gain (> 40 dB): low power drive amplifier	**Low gain (~22 dB): high power drive amplifier (expensive)**
High efficiency in saturation, which drops rapidly at reduced power	**Higher efficiency, which does not drop quickly at reduced power: highly linear device**
Longer, expensive device	**Shorter, less expensive tube**
Can be designed for very high power operation	**Output power is limited though R&D for high power tubes are under way**

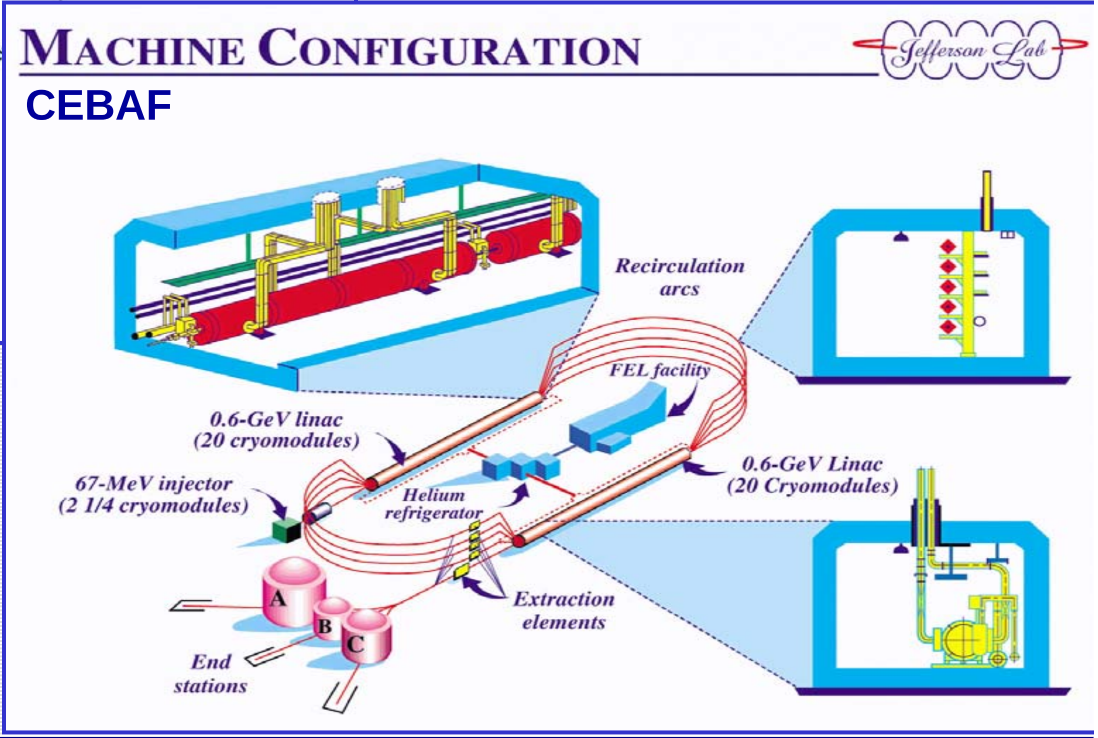


Normalized characteristics of output power (vertical axis) vs. drive power (horizontal axis) for klystrons (blue, saturating) and IOTs (green, not saturating).

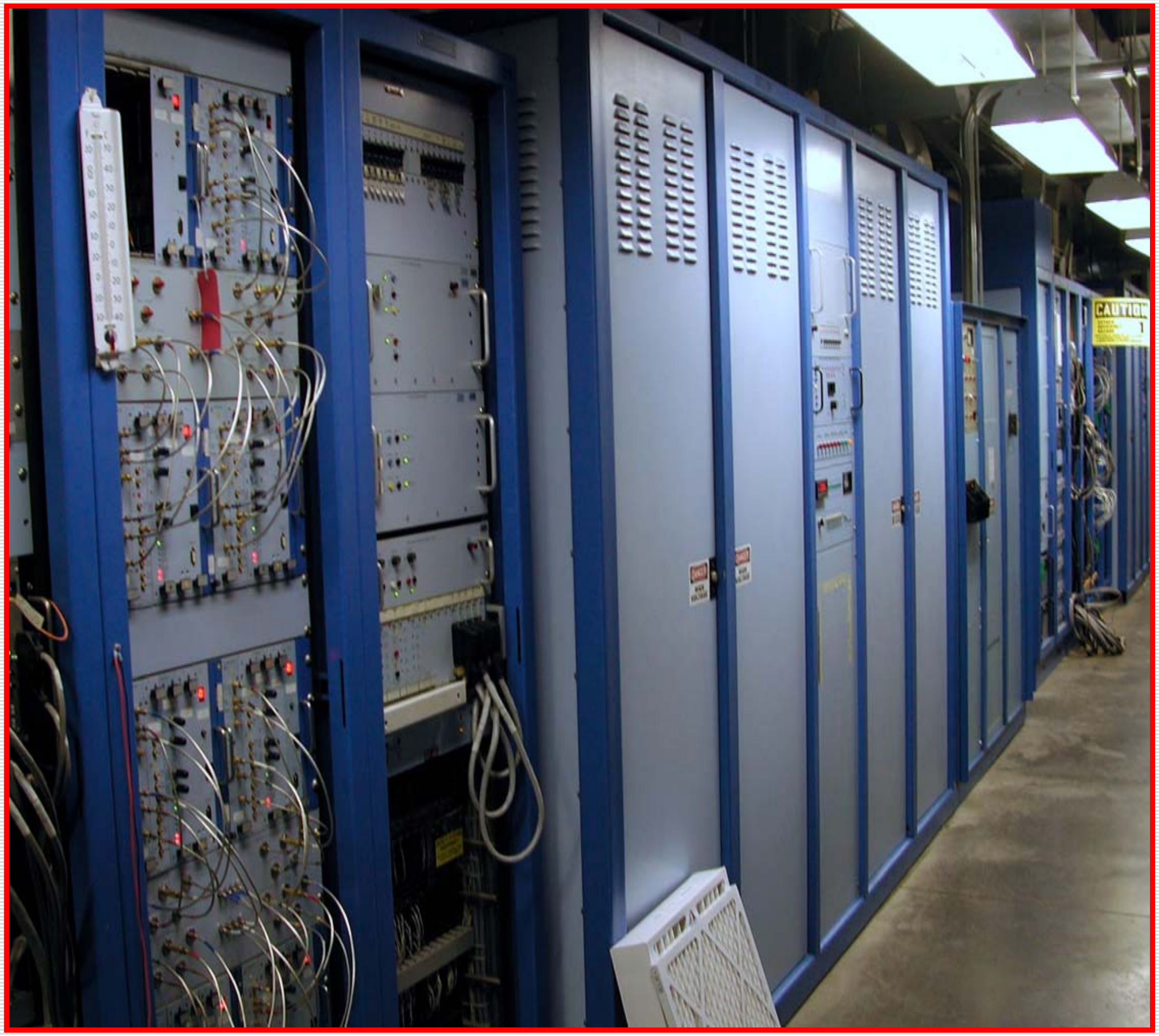


JLab SRF linacs



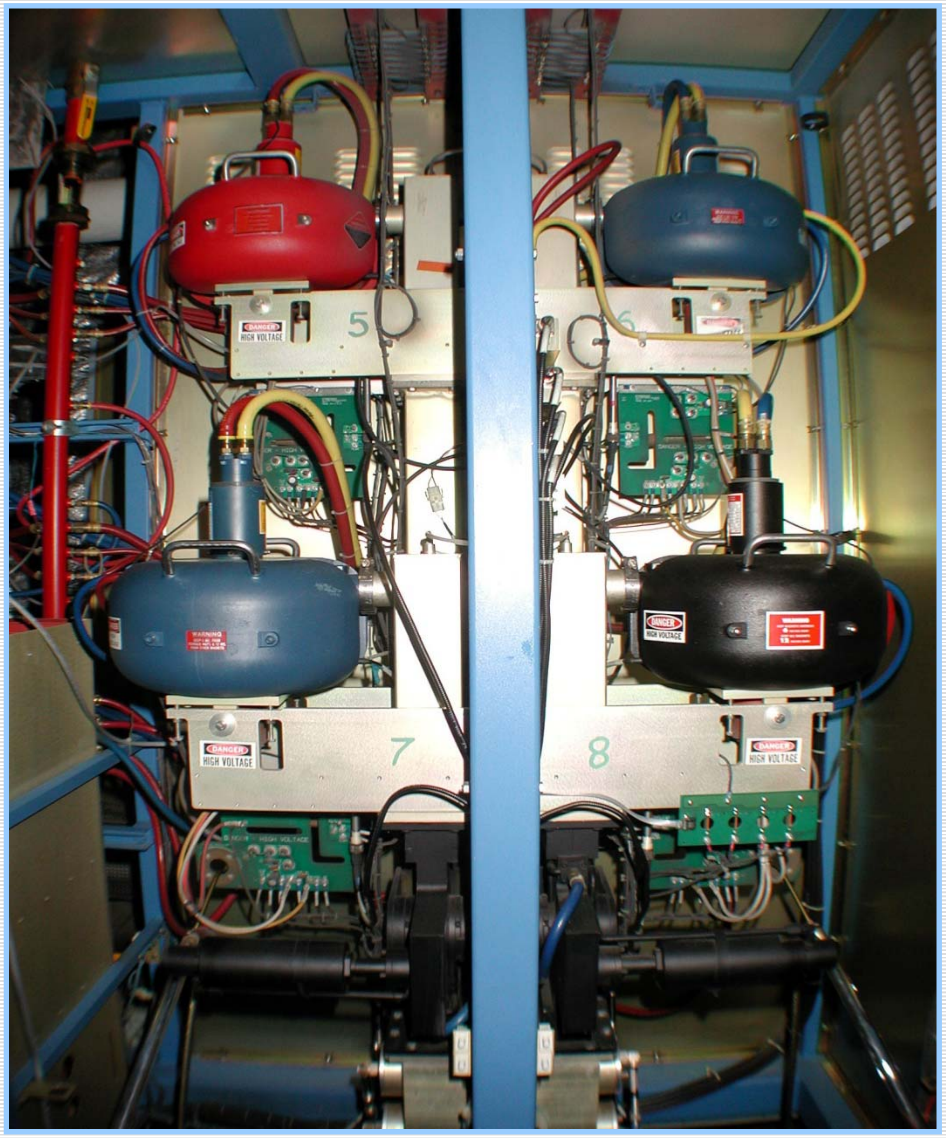


RF zone configuration



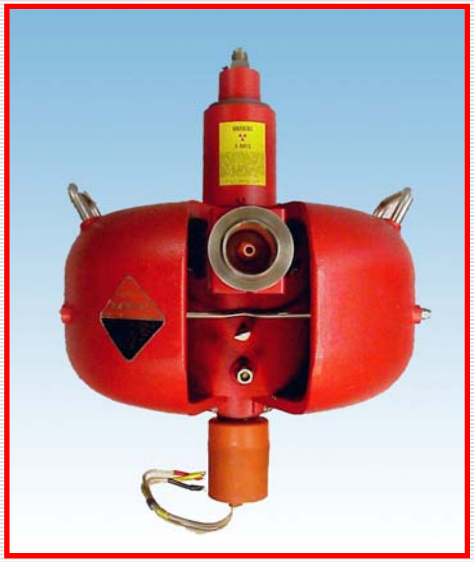
- **3 control racks**
- **5 racks for klystrons: *VKL6811W* (CPI) or *L491* (L3)**
- **Single shared HV power supply**
- **42 systems in CEBAF**
- **3 more in FEL**
- **FEL Injector 2 stand-alone 100 kW klystrons: *VKL7966A* (CPI)**

Klystron configuration



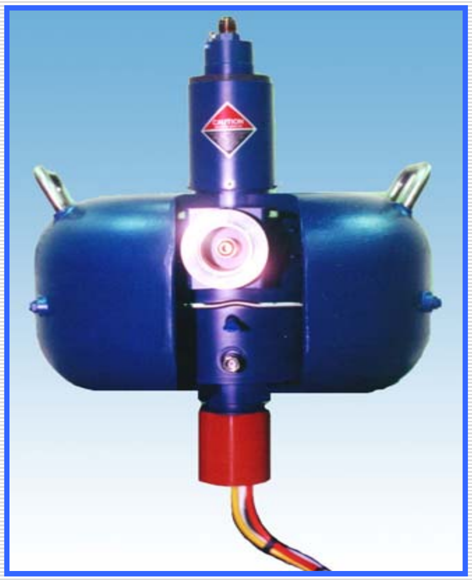
- **8 klystrons per zone**
- **Powered from single HV power supply**
- **Circulators, couplers, etc.**
- **4 waveguides per penetration to tunnel**
- **After addressing initial failure modes, present average lifetime of the klystrons is 165,000 hours**

JLab klystrons



VLK7811W

- Purchased through competitive bid
- Order of 350 units
- 3 year delivery period
- Specifications
  - 5 kW CW
  - 11.6 kV @ 1.33 A
  - 32.4% efficiency (min)
  - 38 dB gain
  - 4 cavity design
  - Coaxial output
  - Permanent magnet focusing
  - Potted gun
- Size limitations



L491

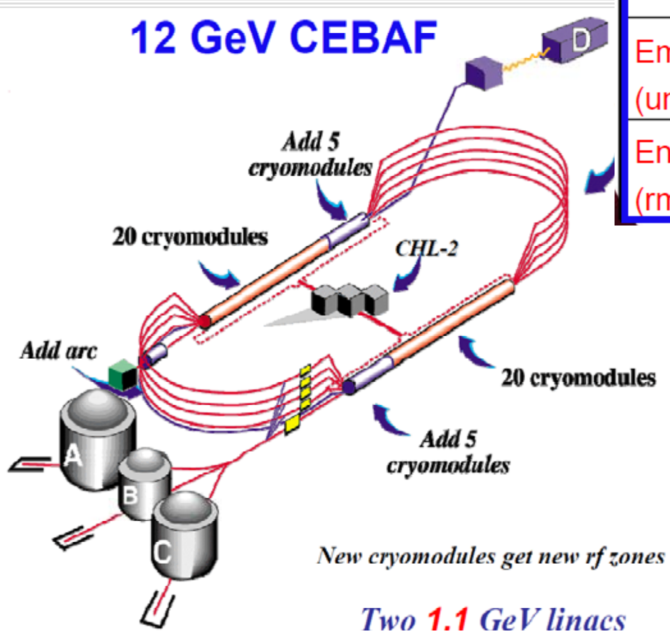
- Replacement from competitive bid
- Multi-year order
- Purchase in lots of 10 or 20 units
- 119 received

VKL7966A

- 110 kWatts
- 33.5 kV @ 6.5 A
- 1497 MHz
- -1dB Bandwidth 14 MHz
- Saturated Gain 55.5 dB
- Efficiency 51 %

CEBAF 12-GeV Upgrade

	6 GeV	12 GeV
Energy to Halls A,B,C / D	6 GeV	11 GeV / 12 GeV
Number of passes for Halls A,B,C / D	5	5 / 5.5 (add a tenth arc)
Duty Factor	CW	CW
Max. Current to Halls A+C / B	200 μA / 5 μA	
Max. Current to Halls A+C / B+D		85 μA / 5 μA
Max. Beam Power	1 MW	1 MW
Emittance at max. energy (unnormalized, rms):	1 nm-rad	10 nm-rad
Energy spread at max. energy (rms)	2.5×10^{-5}	2×10^{-4}

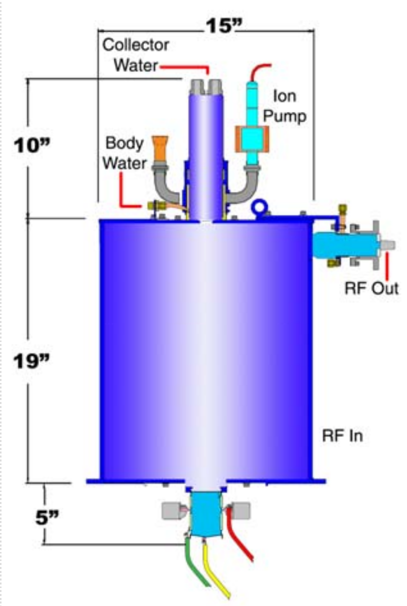


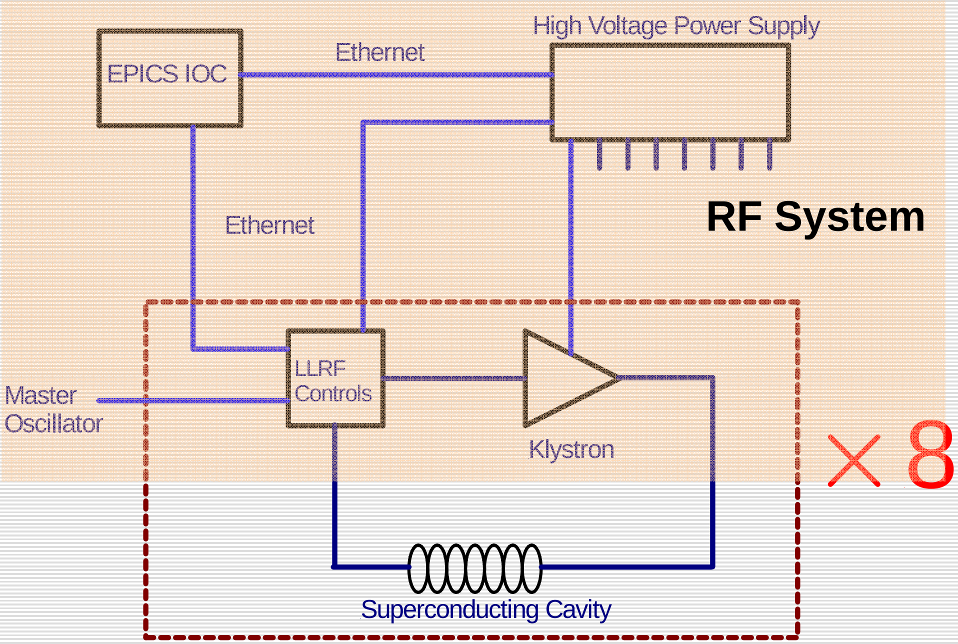
RF for 12-GeV Upgrade

10 new zones of RF power for new accelerating structures:

- **80 new tubes, 10 HVPS**
- **WG network for 80 cavities**
- **Operating freq. 1497 MHz**
- **Operating gradients required >17.5 MV/m**
- **Operating RF power per cavity 13 kW saturated power**

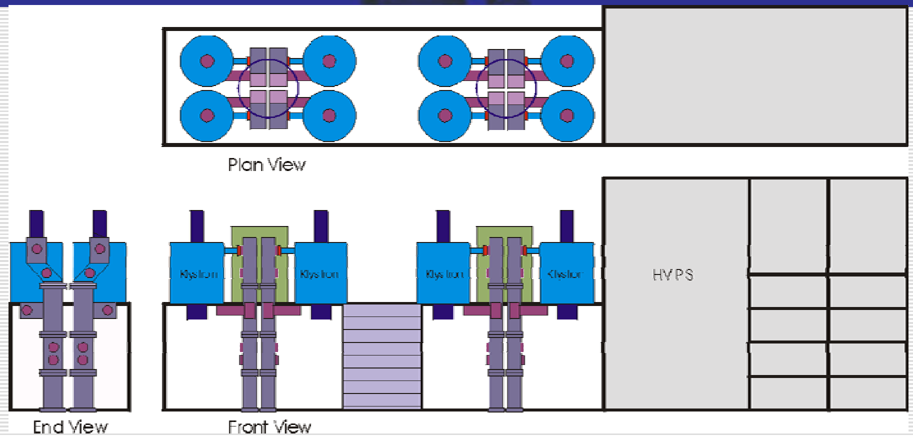
		Fast (<1sec)	*Slow (>1sec)*
Phase Stability (rms)	correlated	0.24°	Infinite
	un-correlated	0.5°	3.0°
Amplitude (rms)	correlated	$2.2x10^{-5}$	NA
	un-correlated	$4.5x10^{-4}$	NA

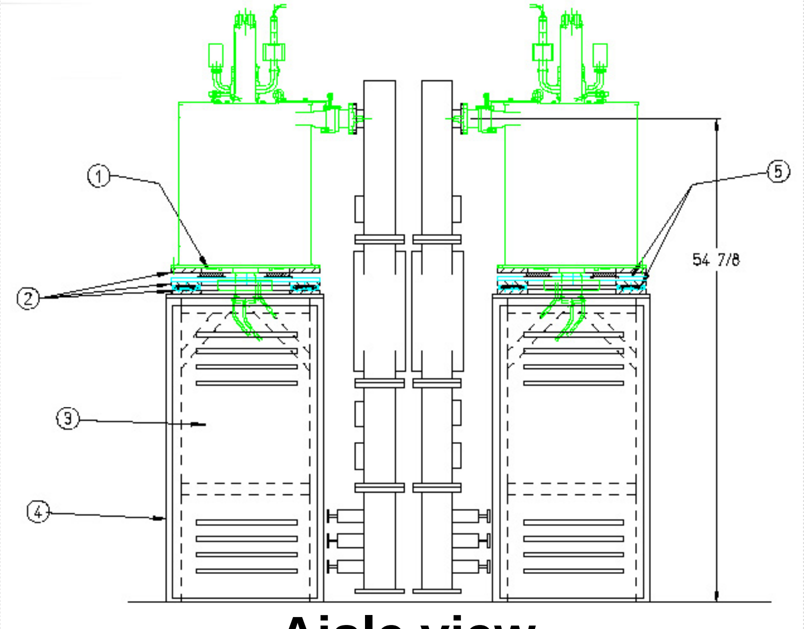




RF layout

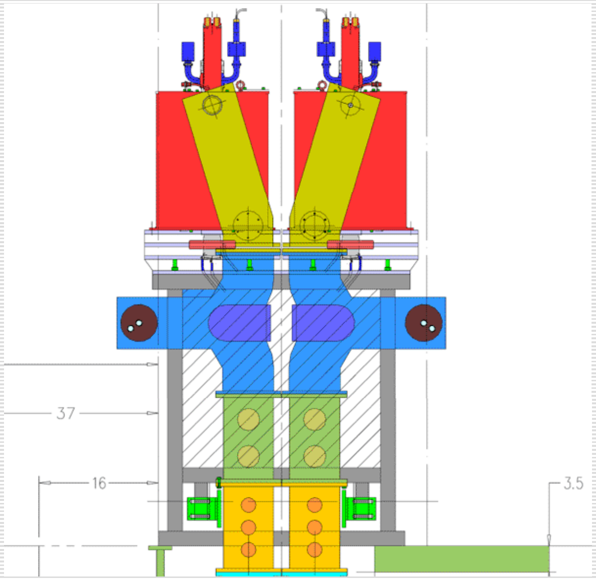
2007 Conceptual





Aisle view

2008 Design Detail

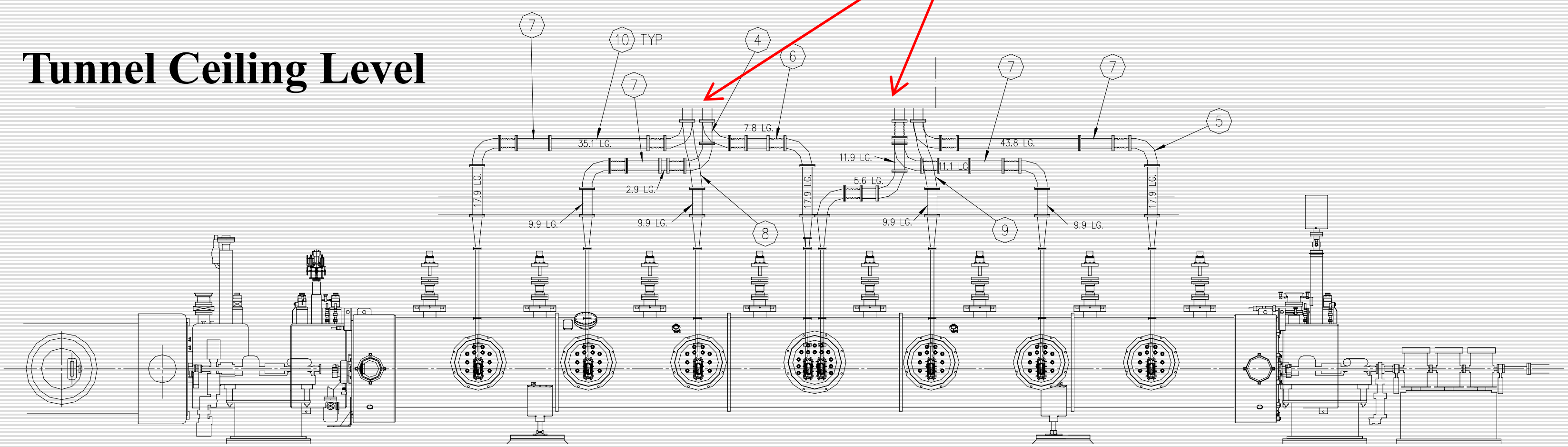


Centerline view

Waveguide layout

Penetrations to Service Bldg.

Tunnel Ceiling Level



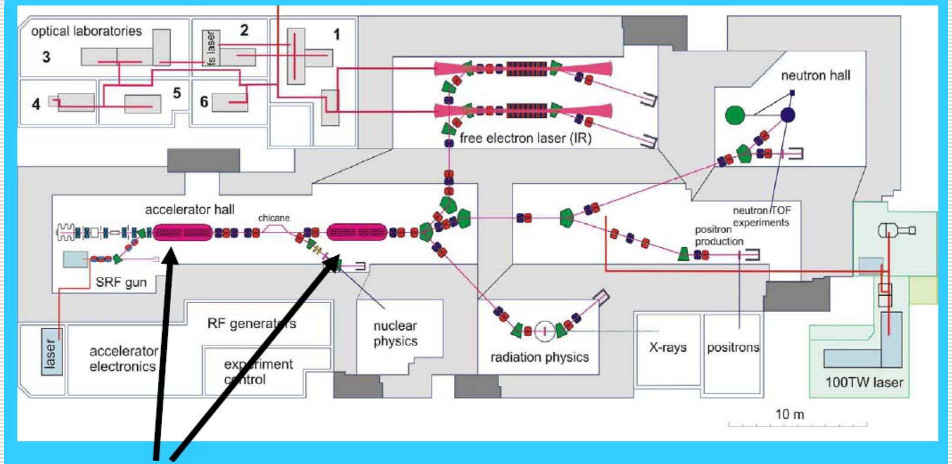
Cryomodule

Tunnel Waveguide

ELBE

ELBE is a multi-purpose facility based on a CW Superconducting RF linac

	Thermionic Gun	SRF Photo Gun
Maximum Energy	40 MeV (CW)	40 MeV (CW)
Bunch Charge	77 pC	77pc / 2.5 nC
Beam Current	1 mA CW	1 mA
Bunch Length (rms)	1 – 10 ps	4 / 20 ps
Transv. Emittance	2/10 mm mrad (rms)	0.5 / 2.5 mm mrad
Max. Rep.Rate	260MHz@0.77pC 13 MHz@ 77pC	13 MHz
Energy Spread	35 keV /55 keV	40 keV



- -Two Cryomodules, equipped with two TESLA (DESY) 1.3 GHz cavities
- -Individially driven systems, one cavity – one klystron
- -Injector: Thermionic Gun (250 kV) + two Bunchers (260 MHz, 1.3 GHz)

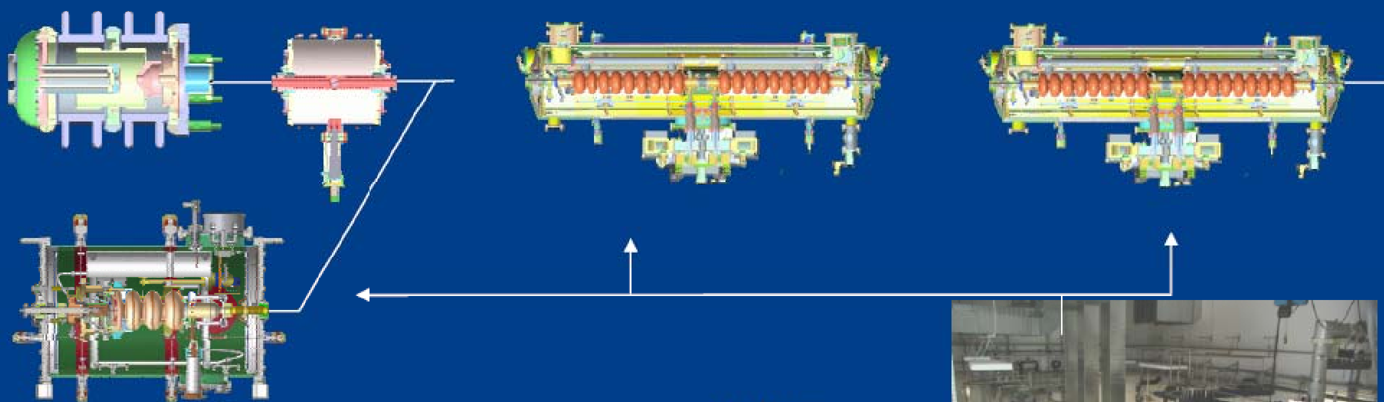
ELBE linac

Thermionic
DC Gun
250 kV
<= 260 MHz
<80 pC
~ 500ps
~10 mm mrad

RF Bunchers
260 MHz
+1,3GHz
compr. ~ 100:1

Linac
1,3 GHz
~20MeV@10 MeV/m
CW

Linac
1,3 GHz
~20 MeV@10MV/m
CW



SRF photo gun
9.5 MeV
<= 13 MHz
80pC / 1nC / 2.5 nC
~ 5-20 ps
~ 1.5-3 mm mrad

Helium
Liquifier
LINDE
200 W @ 1,8 K

Forschungszentrum
Dresden Rossendorf

ELBE-RF

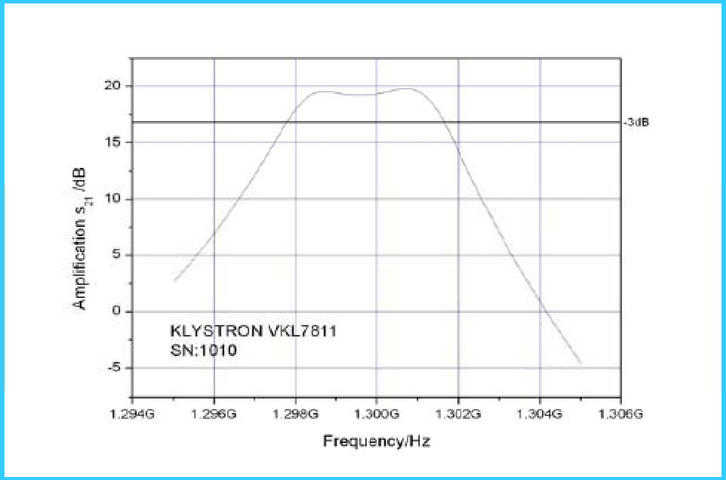
FWKE• Dr.-Ing. H.Büttig • www.fzd.de • Mitglied der Leibniz-Gemeinschaft

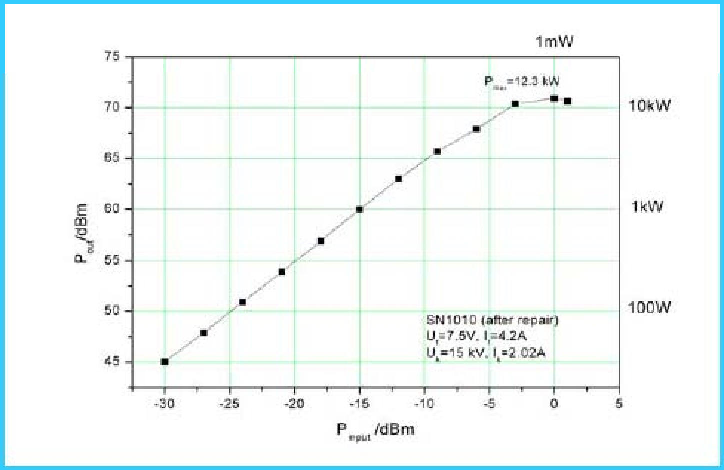
ELBE RF system

Klystron

VKL7811St (CPI)
6-klystrons running

PS: SMPS 15 kV;2.5A
(FuG Rosenheim, Germany)
Water: 46 l/min, 6 Bar

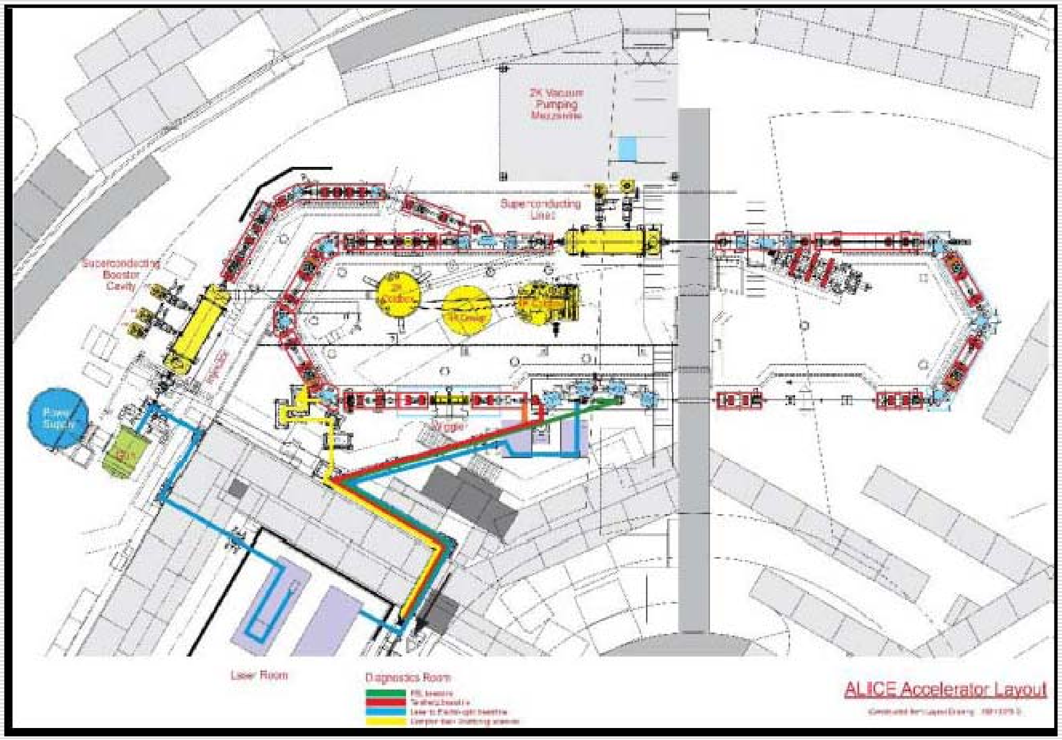




Recently installed a new 30 kW CW system built by Bruker, based on the *CHK51320W* IOT (CPI)

ALICE

Accelerators and Lasers in Combined Experiments(ALICE) is an R&D facility for the development of advanced accelerator systems; from high-intensity electron sources, CW SRF linac cryomodules, short pulse FEL undulators and associated optical diagnostics

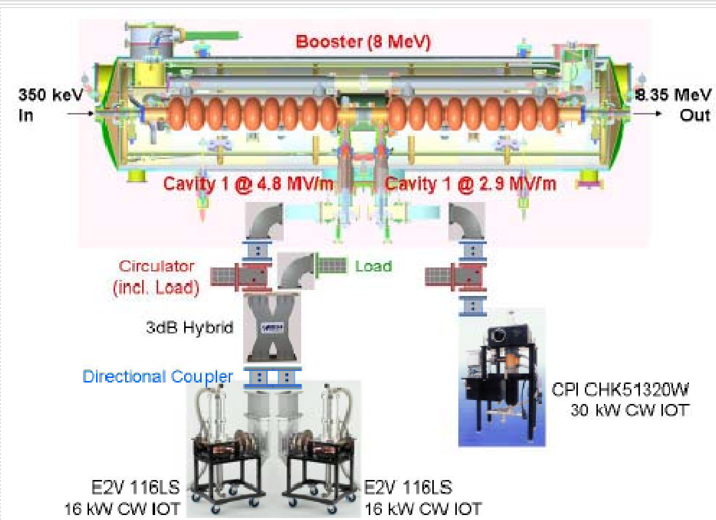


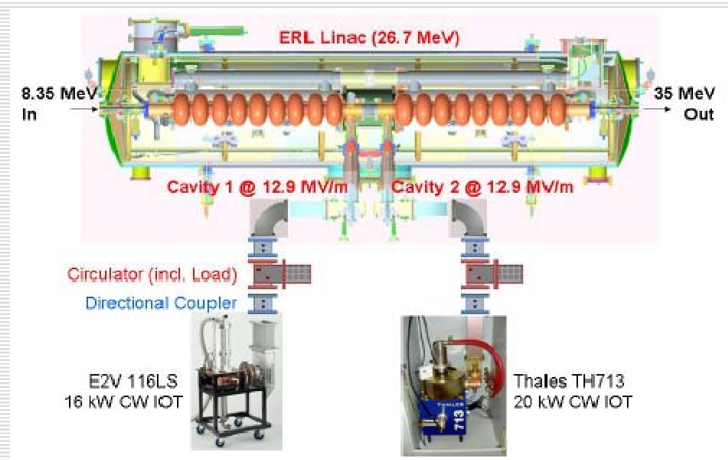
Parameter		Units
Nominal Gun Energy	350	keV
Injector Energy	8.35	MeV
Circulating Beam Energy	35	MeV
RF Frequency	1.3	GHz
Bunch Repetition Rate	81.25	MHz
Nominal Bunch Charge	80	pC
Maximum Train Length	100	μs
Maximum Train Repetition Rate	20	Hz
Maximum Average Current	13	μA

ALICE RF system

	Booster		ERL Linac	
	Cav1	Cav2	Cav1	Cav2
Eacc (MV/m)	4.8	2.9	12.9	12.9
Qo	$5x10^9$	$5x10^9$	$5x10^9$	$5x10^9$
Qe	$3x10^6$	$3x10^6$	$7x10^6$	$7x10^6$
Power (kW)	32	20	6.2	6.2
Power Source	2 x e2v	CPI	e2v	Thales

0.1ms bunch trains @ 20 Hz repetition rate

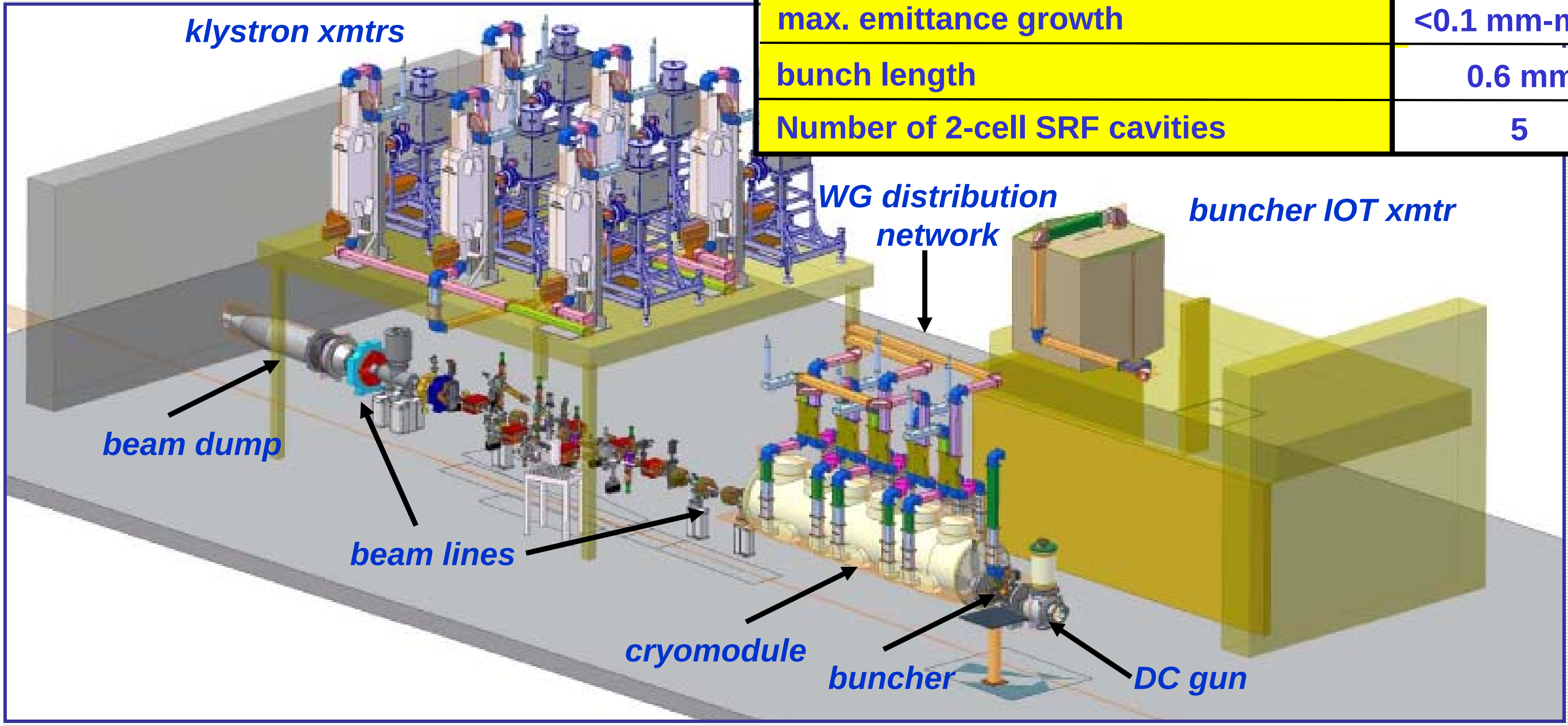




Example: Cornell ERL

Parameters

max beam current at q = 77 pC	100 – 33 mA
beam energy gain	5 – 15 MeV
bunch repetition rate	1.3 GHz
transverse emittance	< 1 mm-mrad
max. emittance growth	<0.1 mm-mrad
bunch length	0.6 mm
Number of 2-cell SRF cavities	5



Cornell ERL injector RF

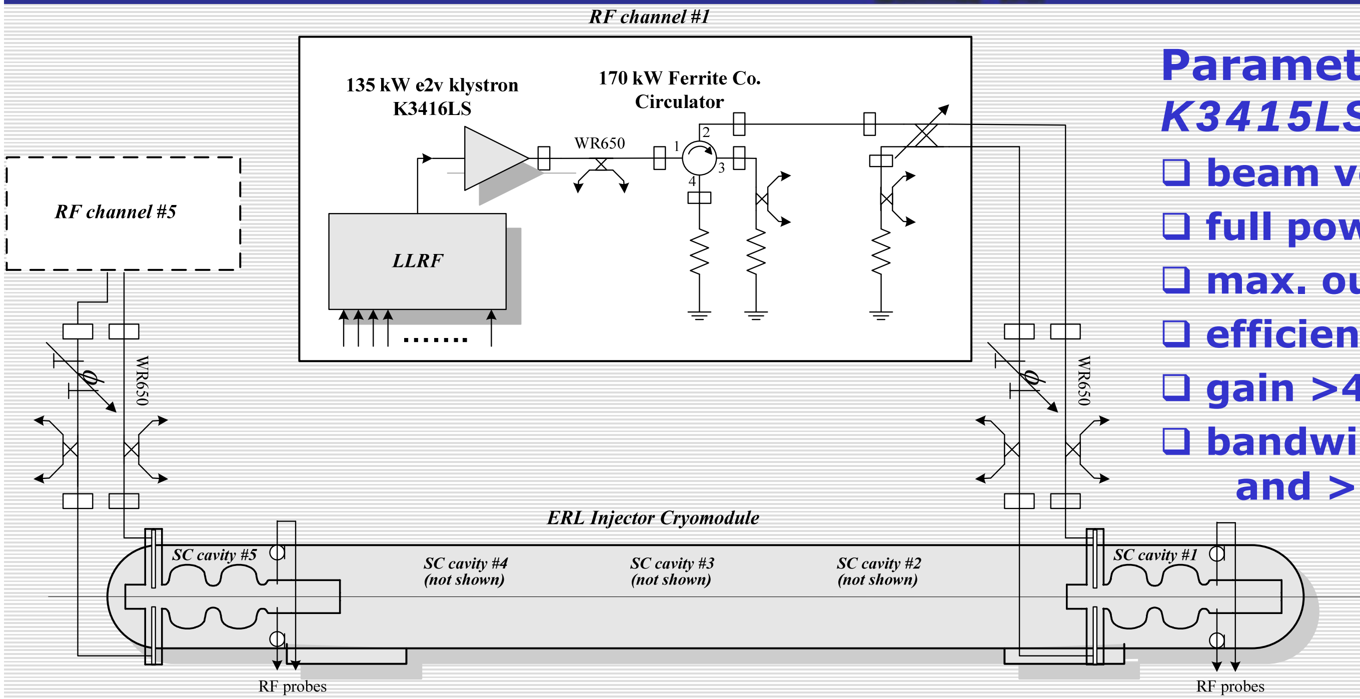
INJECTOR CRYOMODULE RF SYSTEM

- Five 2-cell SC cavities, each delivering up to 100 kW of RF power to beam
- Five identical RF channels
- RF power is delivered to cavities via twin 50 kWCW input couplers
- RF power delivery system includes an adjustable short slot hybrid and a motorized 2-stub WG phase tuner
- 170 kWCW circulators manufactured by the Ferrite Co.
- Two production input couplers reached maximum RF power level of 61 kW on a coupler test stand
- Six klystrons K3415LS manufactured by e2v, all tested at the factory and at Cornell

Specifications of the ICM RF system

Number of cavities	**5**
Accelerating voltage per cavity	**1 – 3 MV**
2-cell cavity length	**0.218 m**
***R/Q* (linac definition)**	**222 Ohm**
Qext	**4.6×10^4 – 4.1×10^5**
RF power per cavity	**100 kW**
Maximum useful klystron power	**≥ 120 kW**
Amplitude stability	**9.5×10^{-4} (rms)**
Phase stability	**0.1° (rms)**

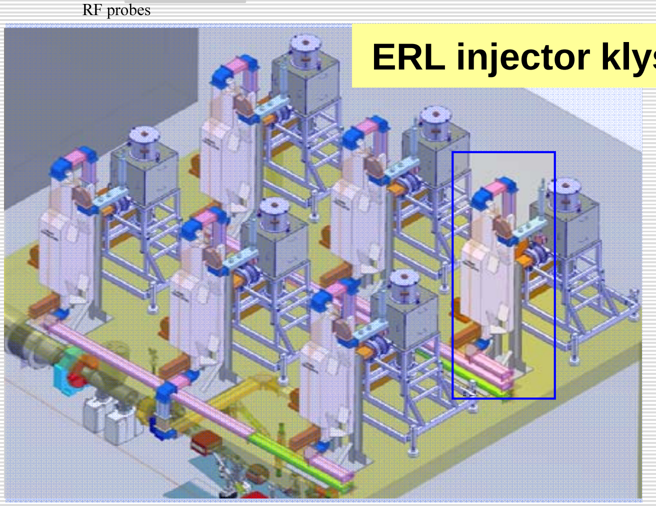
Cornell ERL injector RF

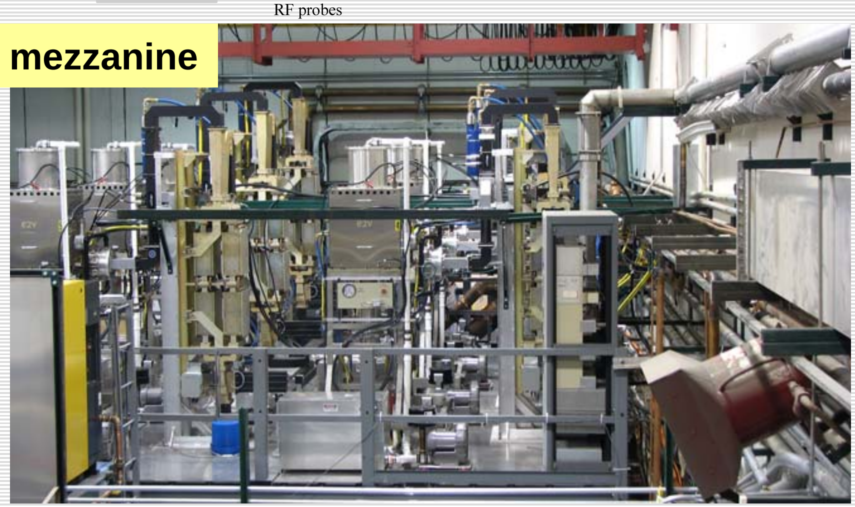


Parameters of the 7-cavity *K3415LS* klystron (e2v):

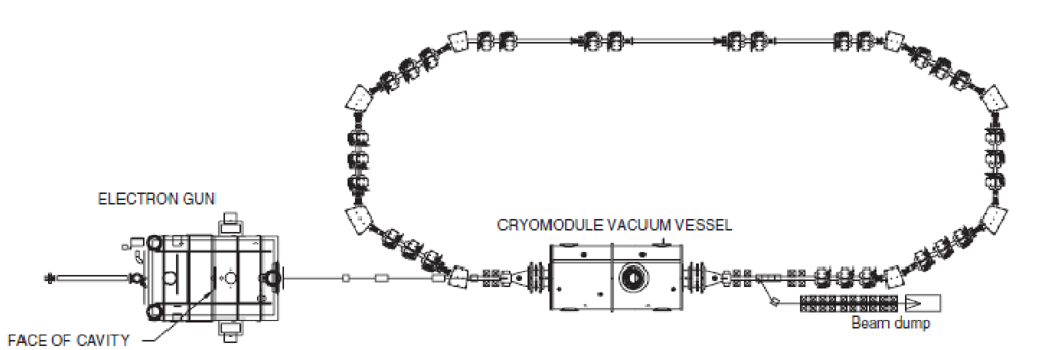
- beam voltage 45 kV @ 5.87 A
- full power collector
- max. output power 135 kW
- efficiency >50%
- gain >45 dB
- bandwidth >±2 MHz @ 1 dB
  and >±3 MHz @ 3 dB

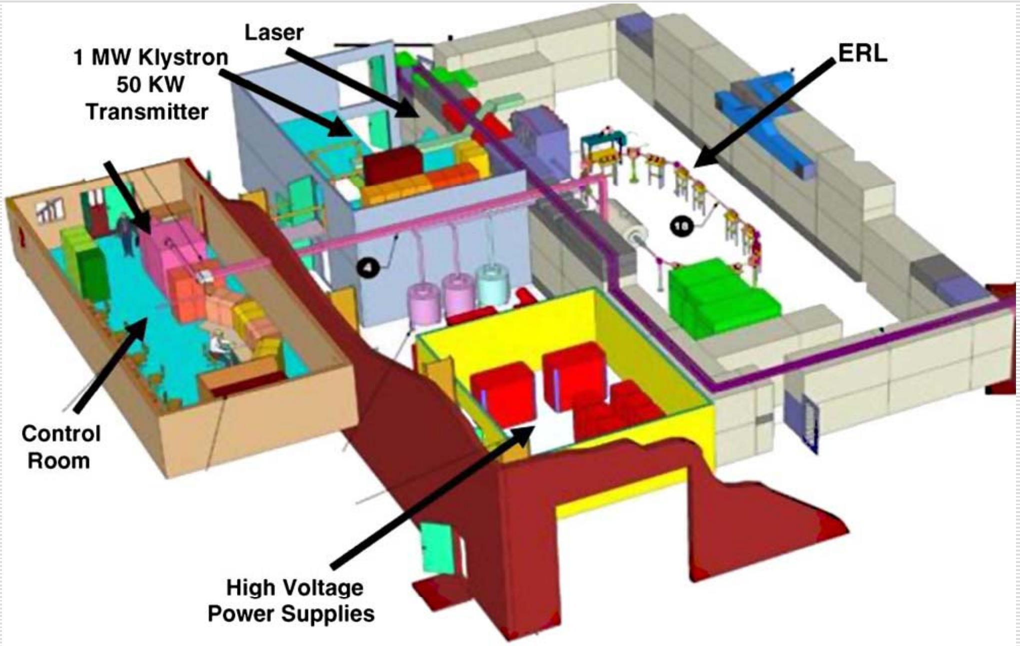
ERL injector klystron mezzanine





Electron cooler for RHIC





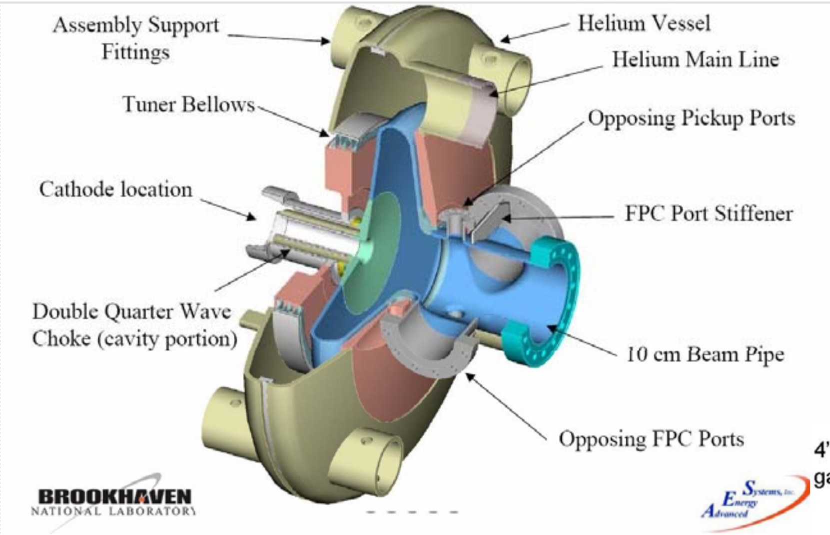
Prototype ERL

Electron cooling is a key component in RHIC II. Cooling gold beams at 100 GeV/nucleon require an electron beam energy of 54MeV and a very high average current of about 200 mA. Future projects such as eRHIC (electron-ion collider) push the operational current to ~500mA at 20 nC bunch charge or higher.

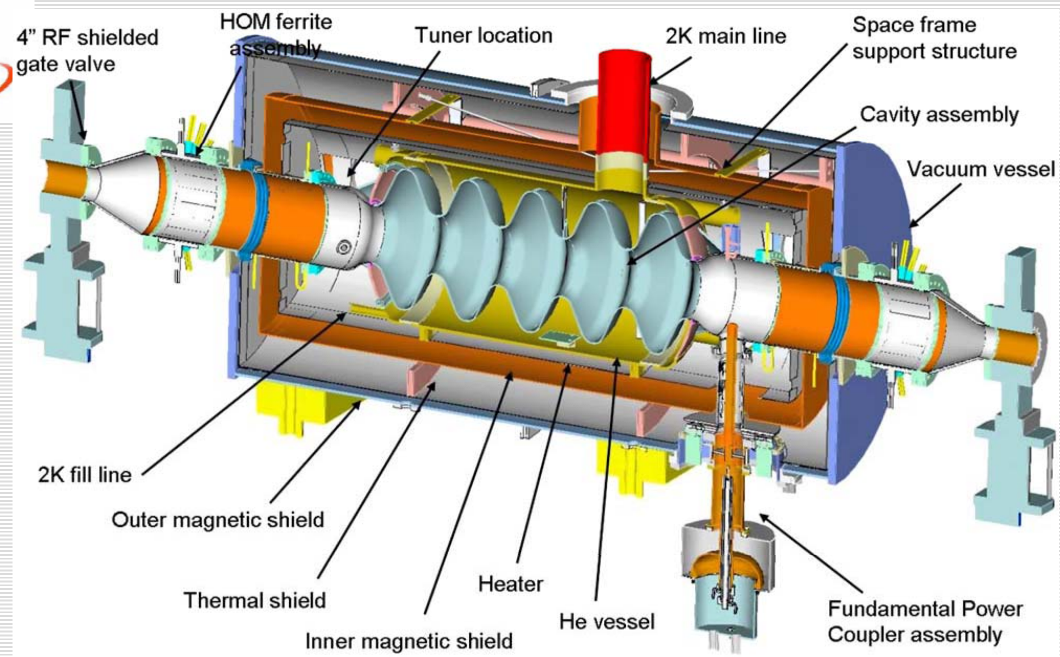
A prototype ERL is a first step towards an ampere class electron cooler. The ERL will consist of a 703.75MHz, 2MeV SRF gun as an injector to the five-cell linac cavity which will accelerate the beam to about 20MeV.

Electron cooler for RHIC

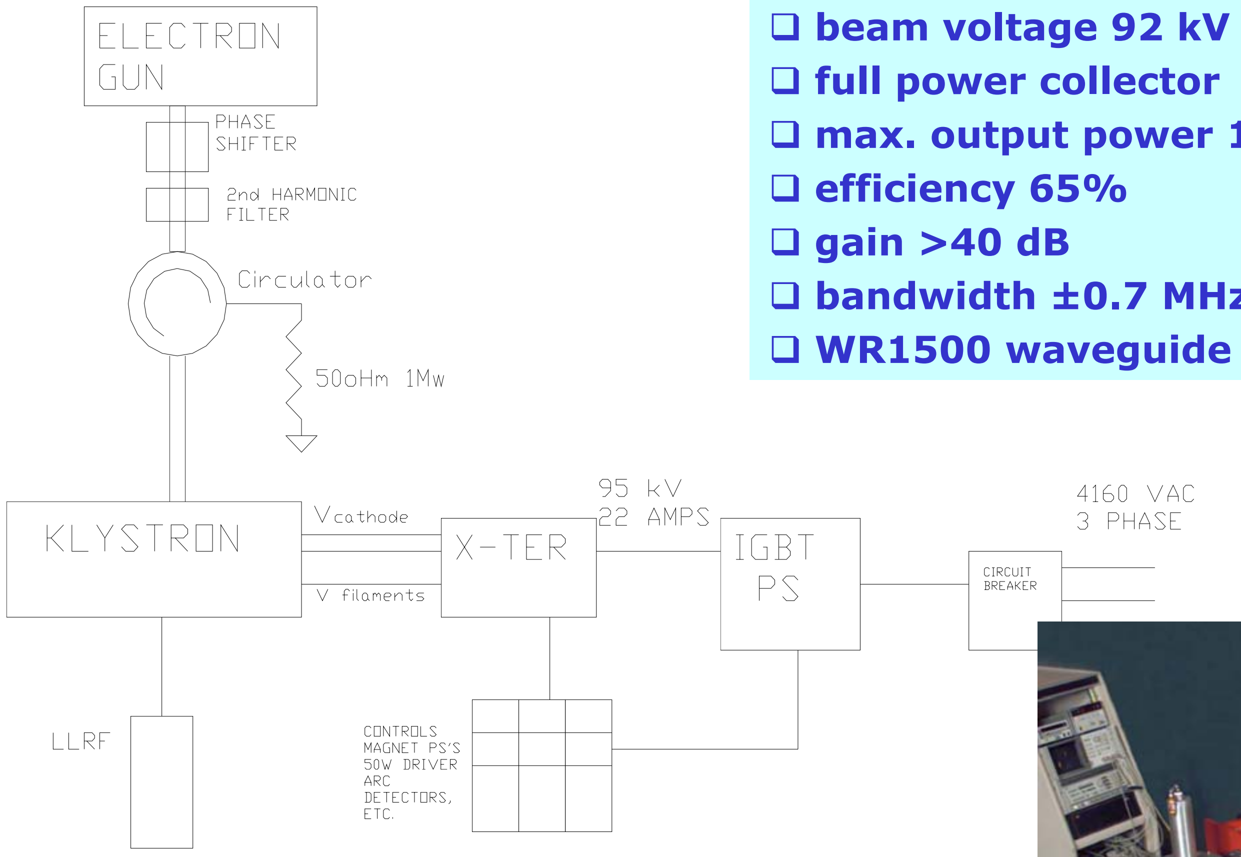
SRF gun



ERL cryomodule



1 MW RF for SRF gun

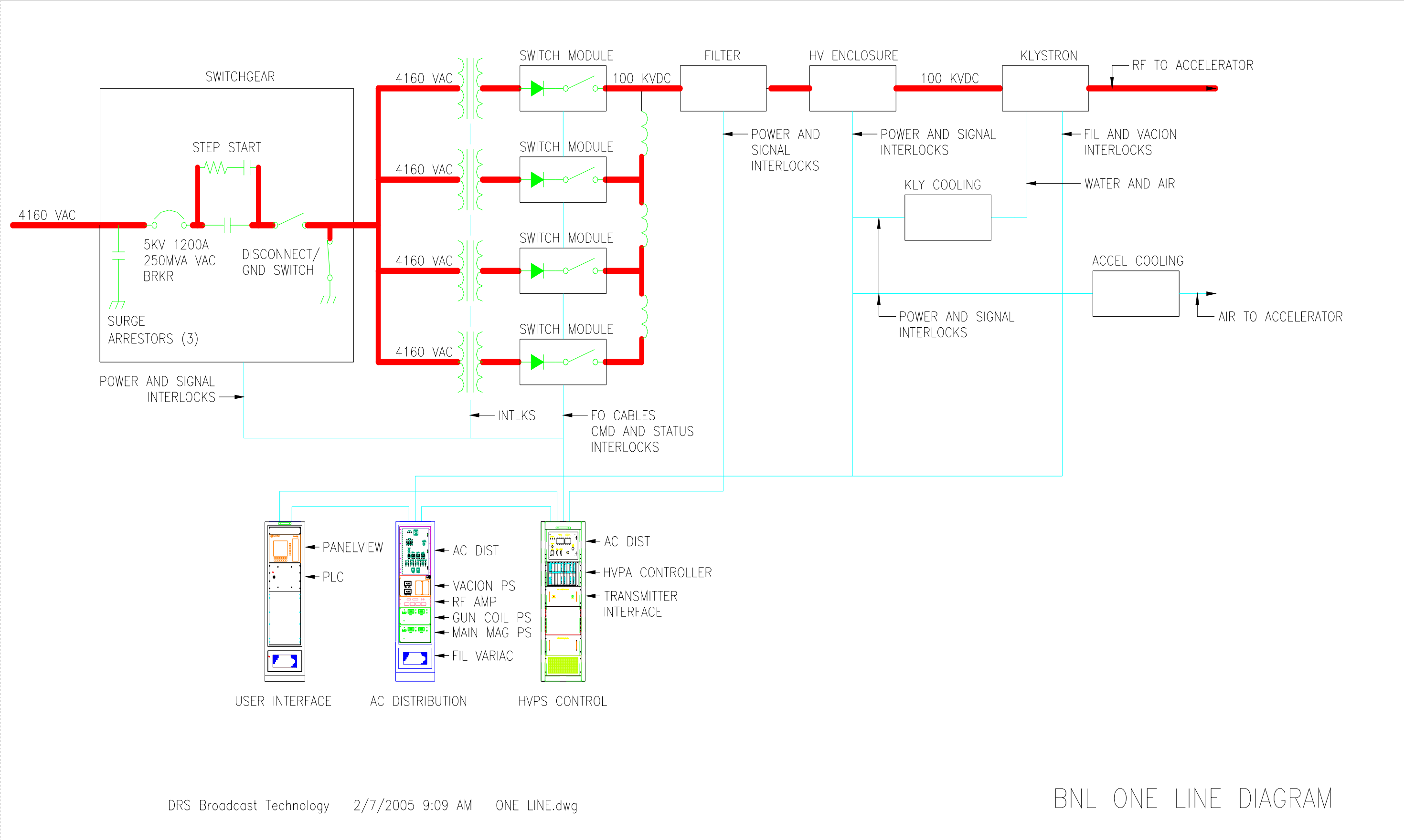


Parameters of *VKP-7952B* klystron (CPI):

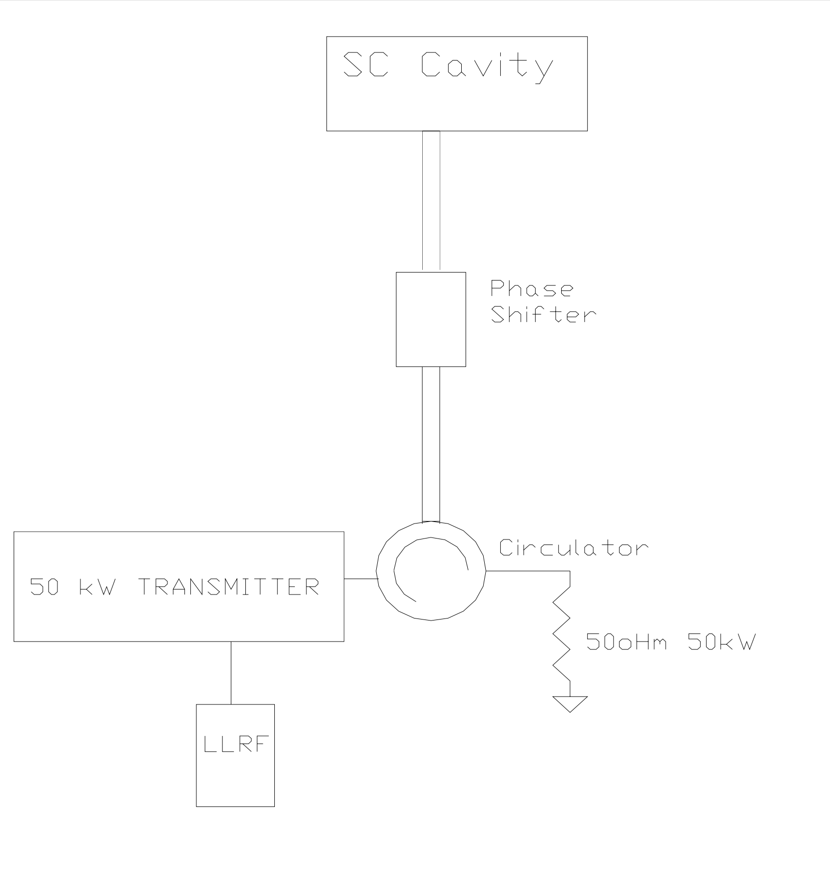
- beam voltage 92 kV @ 17.1 A
- full power collector
- max. output power 1000 kW
- efficiency 65%
- gain >40 dB
- bandwidth ±0.7 MHz @ 1 dB
- WR1500 waveguide output

HVPS

IGBT based system that uses a Fast Shut Down Mode (FSDM) instead of a crowbar. Transmitter was manufactured by Continental Electronics.



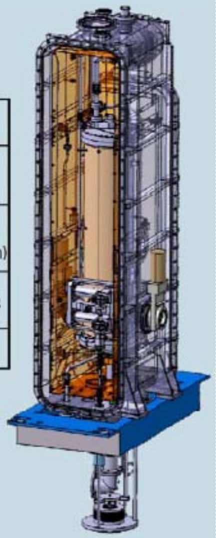
50 kW RF for ERL cavity

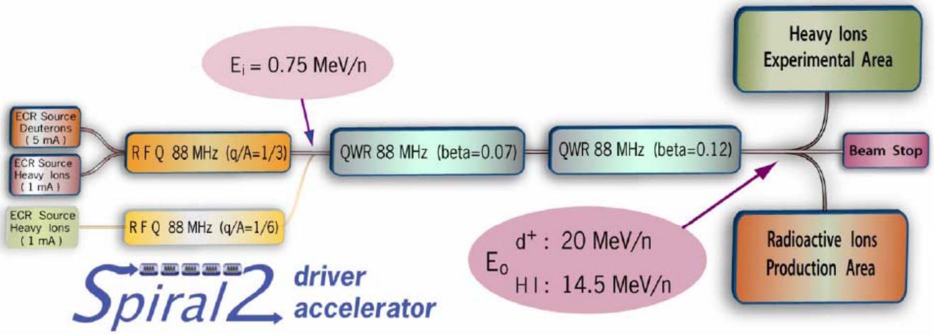


- broadcast transmitter manufactured by Thomson-BM (former Thales-BM)
- modified version TH793 Thales broadcast IOT

SPIRAL-2 project

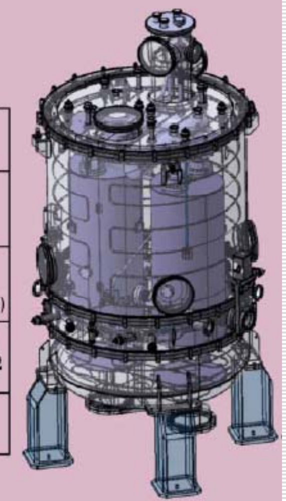
β = 0.07	
E_{peak}/E_{acc}	5.0
B_{peak}/E_{acc}	8.75 mT/(MV/m)
R_s/Q	632 Ω
$Q_0 \times 10^9$	2.2



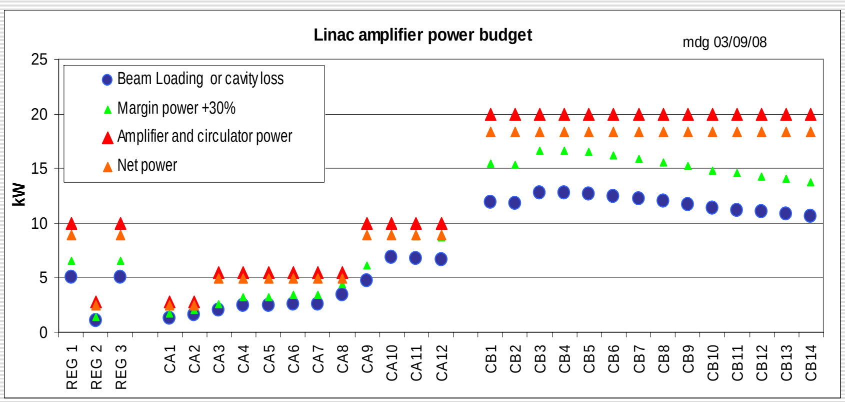


- Radioactive beam facility
- Protons: 33 MeV, 5 mA; deutrons: 40 MeV, 5 mA; heavy ions: 14.5 MeV/u, 1 mA
- 12 $\beta = 0.07$ QWR cavities
- 14 $\beta = 0.12$ QWR cavities
- Independently phased cavities for wide velocity acceptance and output energy optimization for each ion species

β=0.12	
E_{peak}/E_{acc}	5.5
B_{peak}/E_{acc}	10.1 mT/(MV/m)
R_s/Q	521 Ω
$Q_0 \times 10^9$	1.7

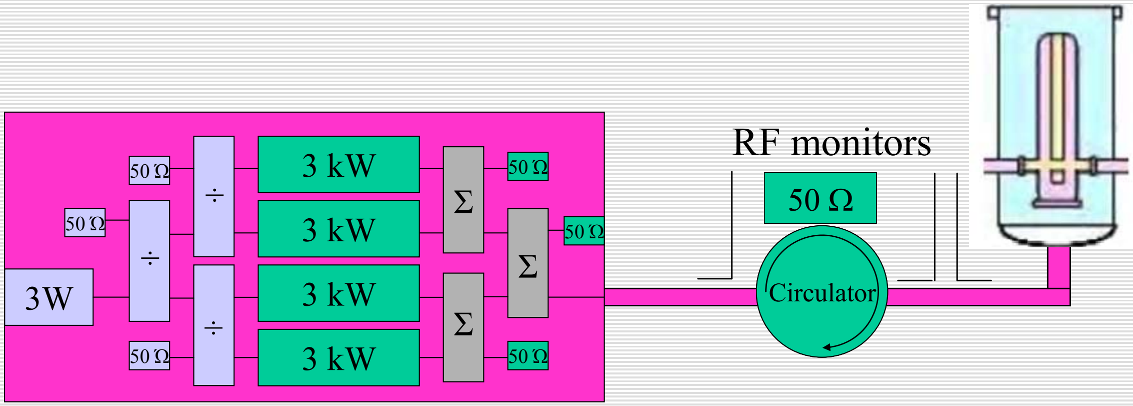


SPIRAL-2 RF (THP048)

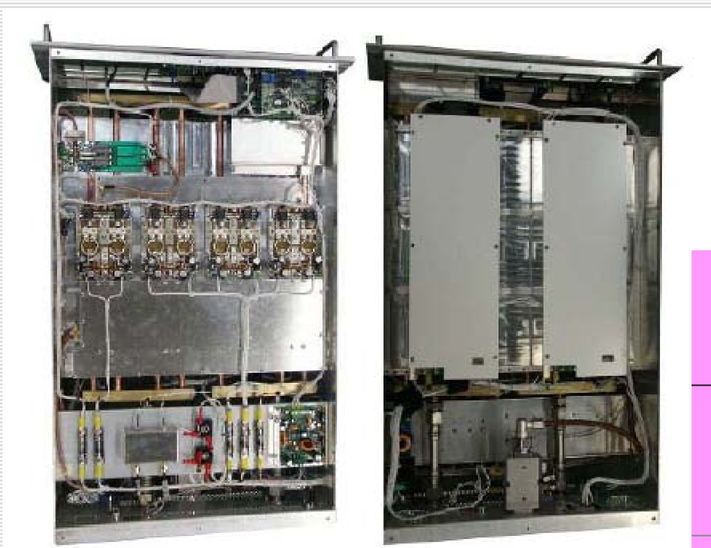


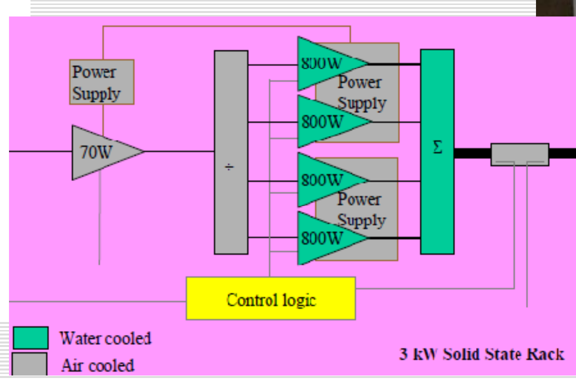
- Utilized power equipment developed for FM market
- 3, 5.5, 10 & 20 kW amplifiers are available
- 3 1/8" 50-Ohm transmission line, air cooled
- Test bench was designed and operated up to 20 kW
- The 10 kW prototype has been used at IPN-Orsay for $\beta = 0.12$ cryomodule test
- Class C amplifiers

SPIRAL-2 RF system



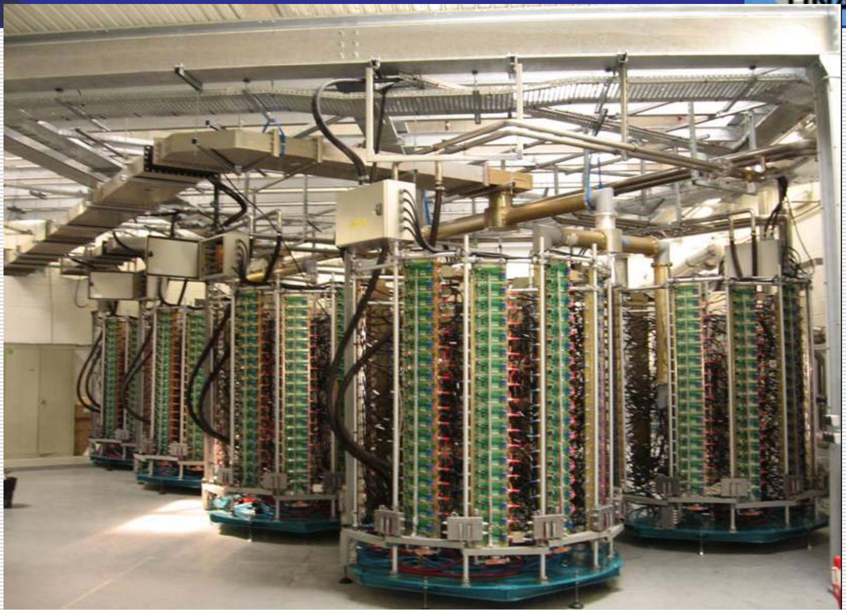
10 kW amplifier architecture. Circulators and dummy load are outside the amplifier cabinet, at high power level. Green elements are water cooled.





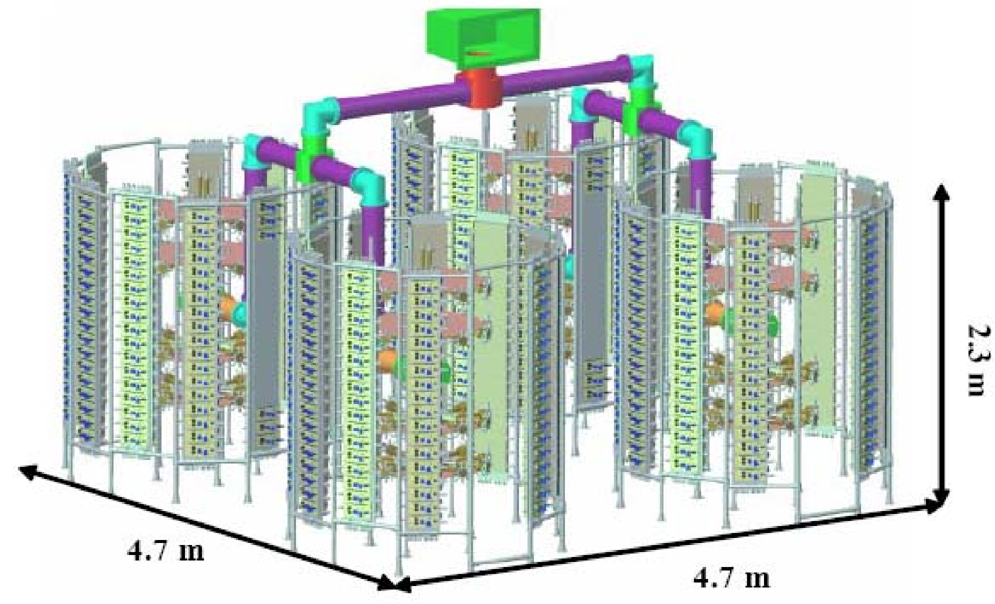
Two 10 kW amplifiers.

SOLEIL solid state HPA



Could not resist to mention:

- **180 kW CW solid state amplifier for SOLEIL storage ring based light source (France)**
- **352 MHz**
- **very reliable and stable operation**
- **efficiency ~50%**



Future projects

More and more future projects are based on CW superconducting RF technology.

Here is a sample list of such projects that utilize L band SRF linacs and will require medium to high power CW RF systems:

STARS (BESSY)
ERL@CESR (Cornell)
KEK ERL
0.5 MW drive linac (TRIUMF)
WiFEL (Wisconsin)

Summary

- CW SRF linacs are used for a wide variety of scientific applications form nuclear physics to light source facilities to radio isotopes production.
- In all machines presented in this talk a simple architecture with one RF high power amplifier per cavity is used. Reasons: flexibility, available RF power sources, requirements to fiels stability, efficiency of RF system, …
- Most of high-β linacs operate in L band. UHF band is left for ampere-class machines. IOTs successfully compete with klystrons at medium power levels due to their better efficiency and linearity.
- Solid state amplifiers are rapidly becoming the technology of choice in VHF band at medium power levels and making way into UHF and L bands (though they are still pricey and not very efficient there.)
- There are more CW SRF linac based projects under consideration at different laboratories.

Acknowledgement

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

C. Hovater (Jlab)

T. Powers (JLab)

H. Buettig (Rossendorf)

P. McIntosh (Daresbury)

A. Zaltsman (BNL)

M. Di Giacomo (GANIL)

R. Laxdal (TRIUMF)

End of talk

Additional slides

Precision HV PS (an example)

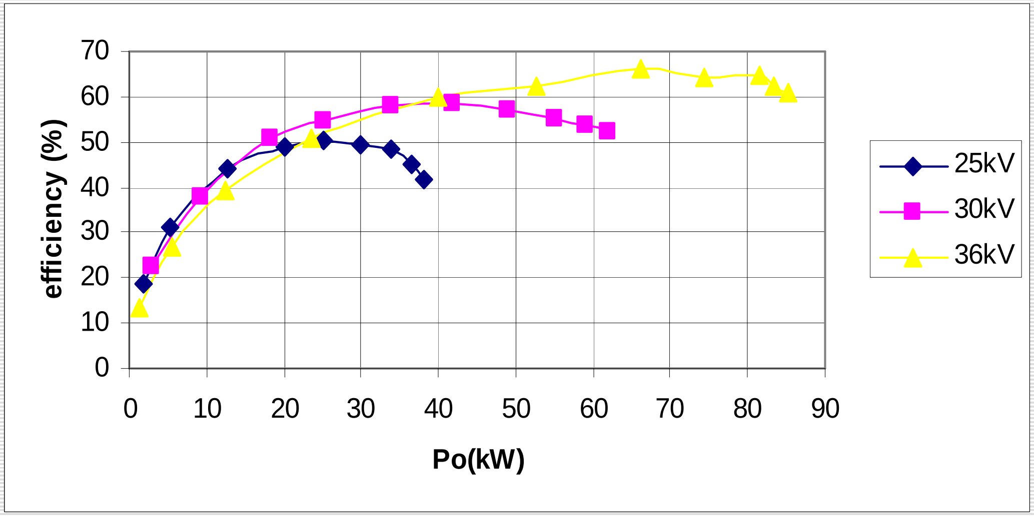
LAMBDA developed a precision 75 kW, 25 kV switching HVPS for a klystron amplifier (reported at PAC'07)

Output Voltage Range:	-10 to -25kV
Output Current:	0 to 4A max
Average Power:	75kW
Ripple and noise:	<0.015% p-p
Efficiency:	90%
Power factor:	0.92
Stability:	10ppm/°C
Load regulation:	0.0001%
Line regulation:	0.0001%
Stored energy:	7.5J

IOT manufacturers: CPI

Features:

- Compact design
- CW or pulse operation
- 35kW CW or 80 kW pulse
- Easy installation
- Fast tube replacement
  (down time less than 1 hour)
- VSWR 1.3:1



IOT manufacturers: THALE

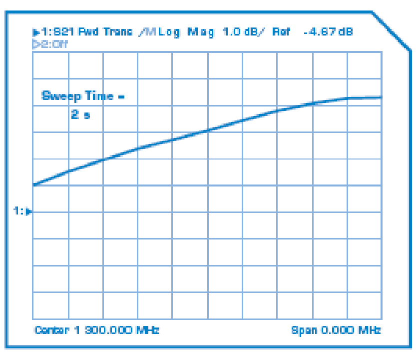
Operating specifications

	CW	Pulsed	
Continuous wave output power	16	30	kW
Frequency range	1.3	1.3	GHz
Bandwidth at –1 dB	≥ 3	≥ 3	MHz
Grid voltage	-100	-90	V
Cathode current	0.93	1.47 (1)	A
Cathode voltage	28.5	33	kV
Gain	20.9	22 (1)	dB
Efficiency	60.4	61 (1)	%
CW input power	146	190 (1)	W
Filament voltage	12	12	V
Filament current	16.5	16.5	A

Maximum ratings

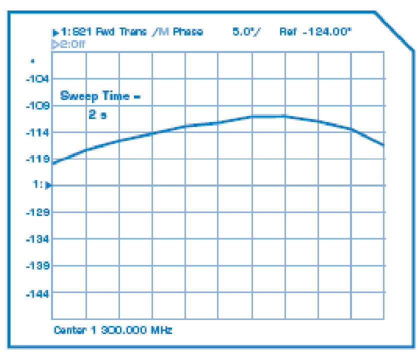
	CW	Pulsed	
Continuous wave output power	20	32 (2)	kW
Input power	200	200	W
Anode dissipation	25	25	kW
Anode voltage	34	34	kV

Gain variation



Delta gain: 3 dB

Phase variation



Delta phase: 7°

From 1 to 16 kW
Sweep time = 2 seconds

IOT manufacturers: e2v

Frequency	1.3GHz
Output Power	16kW
Beam Voltage	<28kV
Efficiency	>60%
Gain	>20dB
Class of operation	B or AB

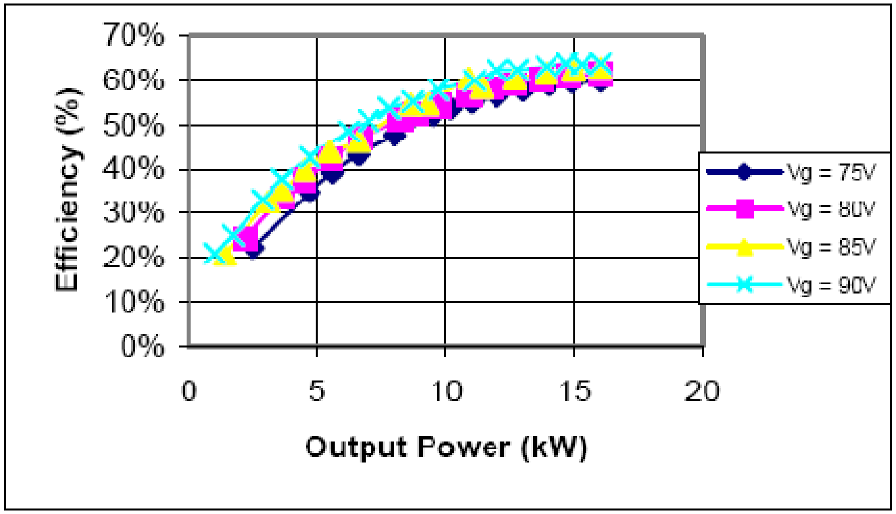


Figure 3: Efficiency versus output power at a beam voltage of 25kV.

Lifetime estimate

- Standard warranty period is 10,000 hrs
- Average life of 1213 broadcast IOTs is 31,700 hrs (for all e2v tubes that have recorded installation and removal date, tubes still in service are not included)