EUROPEAN
SPALLATION
SOURCE

ESS RF SYSTEMS INTRODUCTION

Anders Sunesson RF group leader

Summary

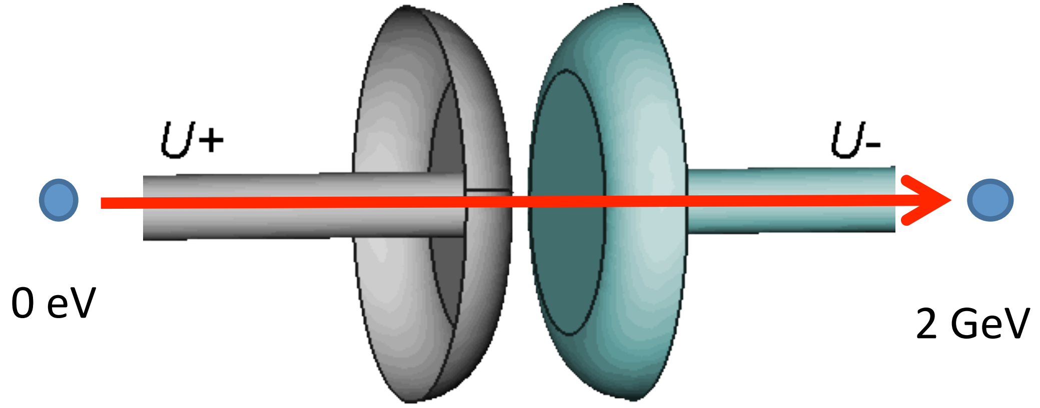
- ESS Linac
- Why do we need RF systems?
- RF systems:
  - High Voltage Power conversion
  - High Power RF Amplifiers
  - Local Protection system/Interlock
  - Low Level RF system
  - Phase reference / Master Oscillator
  - RF Distribution System
- Tests

ESS Linac

- The ESS linac will be the worlds most powerful proton linac
  - Beam pulse width is 2.86 ms and pulse rep rate 14 Hz
  - Protons will be accelerated up to 2 GeV with a beam current of 62.5 mA, beam power 5 MW
- Construction in two stages, stage 1 ready 2019 (570 MeV), stage 2 ready 2022 (2 GeV)
- ESS has a target to be energy efficient – drives design decisions
  - Multi-beam IOT project
  - Cooling water at high temperature
  - Regulation optimization

Particle accelerator – why RF??

- Protons can be accelerated by applying voltage between two electrodes
- The electric field will then accelerate particles if these are let in through a hole
- To get the particle energies needed for ESS the voltage would have to be 2 GV (2 000 000 000 V)

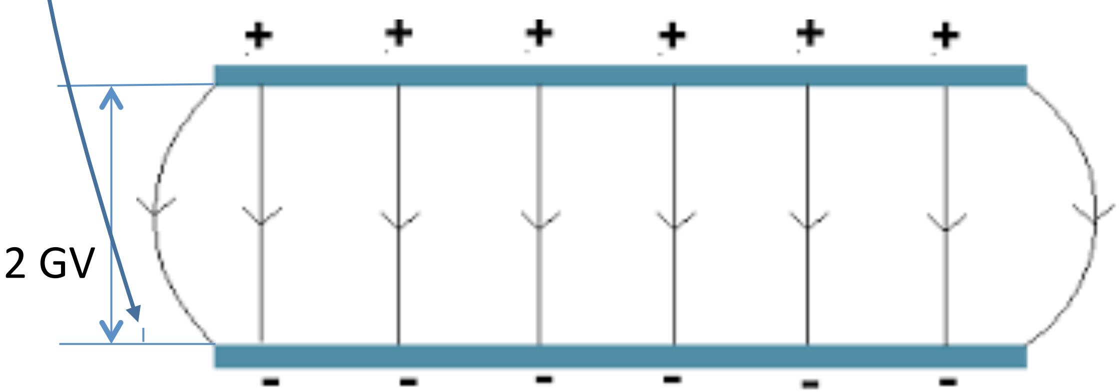


Can be used

- Up to 750 keV
- Cockroft- Walton accelerator

There is a problem though…

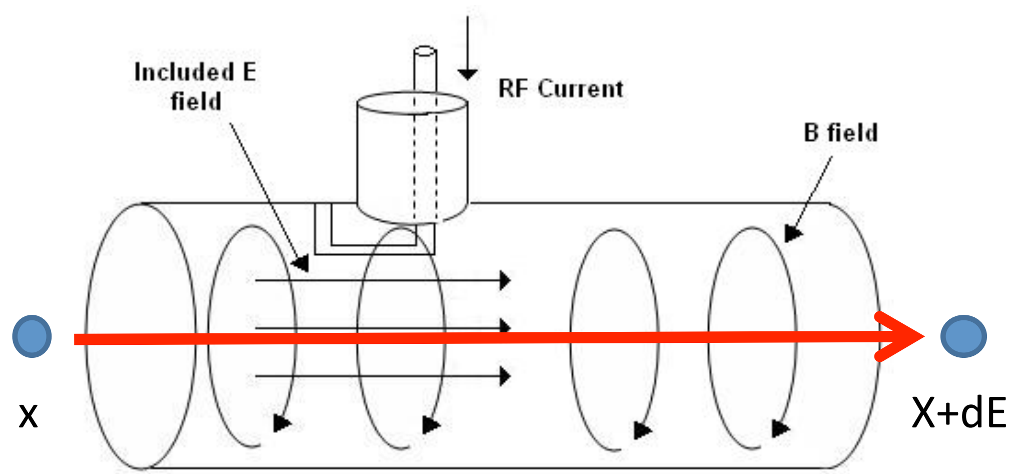
- Only to generate this voltage difficult
- The breakdown strength is a lot lower, up to MV/m
- There would be electric breakdown
- Typical lightning bolt 10-100 MV



Electric field between two parallel charged plates

Alternative: use RF

- Apply RF in a resonant cavity
- This creates an electric field
- A particle gets a kick dE proportional to the fielc
- The field changes direction – no kick
- Then the next particle comes in phase and get a kick
- Particles come in "bunches"



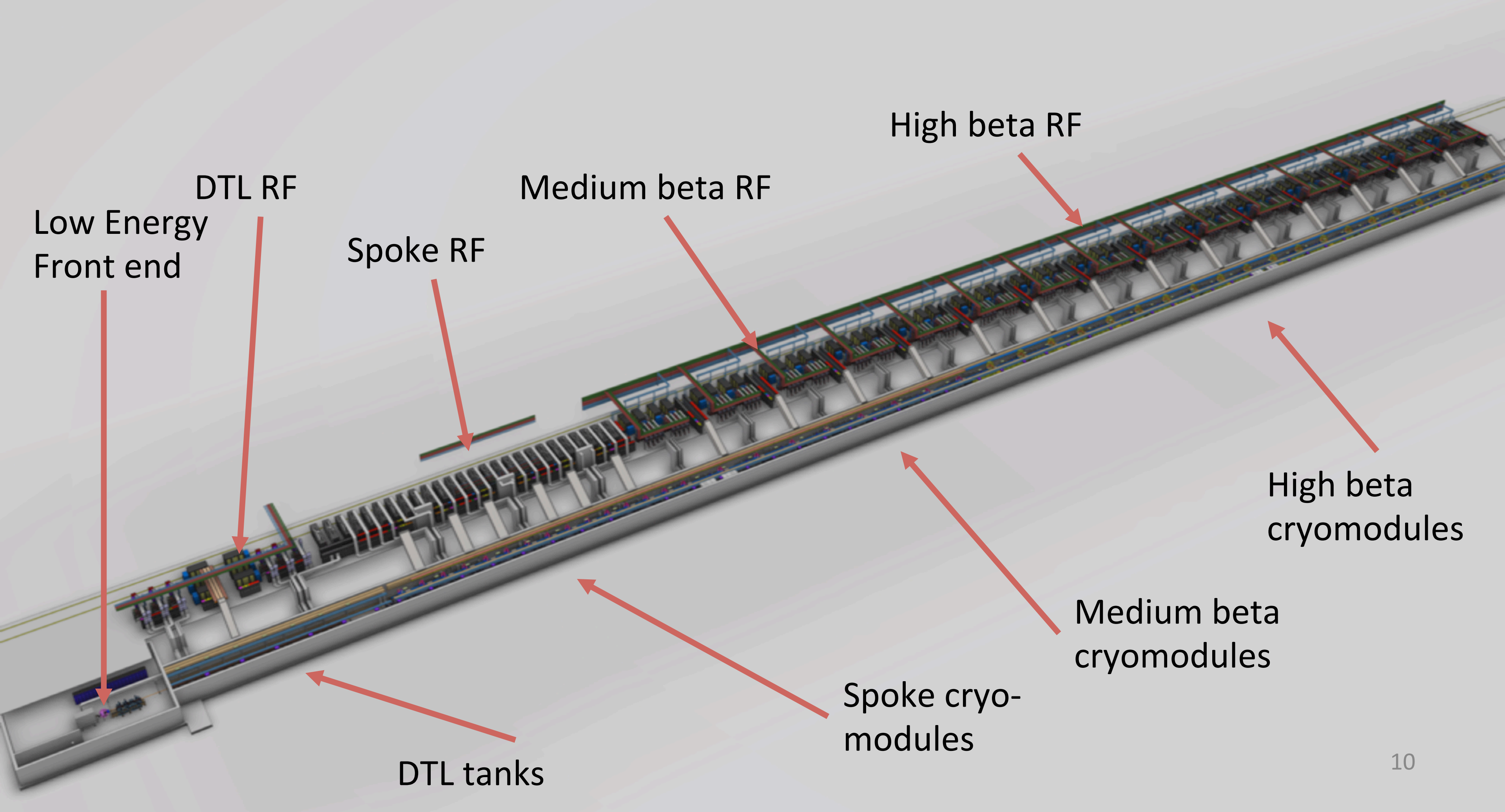
So RF is used (after 1930's)

- Can be stacked one after the other to get more kick
- Scalable, no net field outside – no breakdown outside (can occur inside though)
- Very high particle energies can be reached (CERN LHC 7 TeV)
- More energy possible by just adding cavities

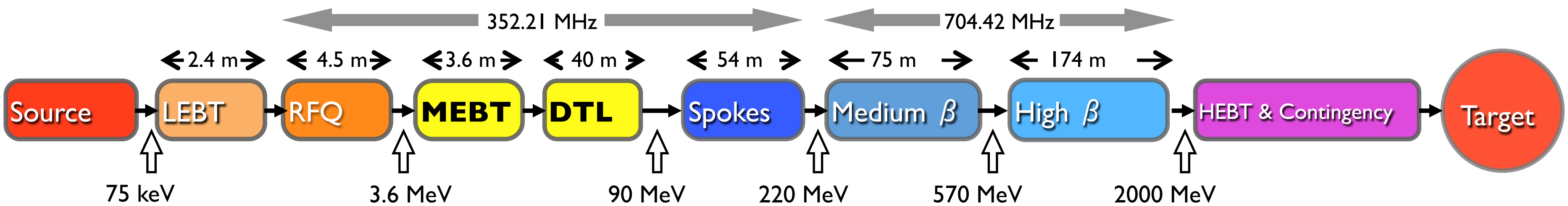
An artists impression of ESS

ESS Linac Layout

- 155 cavities in total, total length ca 350 m until HEBT



RF Requirements



	Energy (MeV)	Frequency / MHz	No. of Cavities	β g	Temp / K	RF power /kW
Source	0.075	-	0	–	~300	–
LEBT	0.075	-	0	–	~300	–
RFQ	3.6	352.21	1	–	~300	1600
MEBT	3.6	352.21	3	–	~300	20
DTL	90	352.21	5	–	~300	2200
Spoke	220	352.21	26 (2/CM)	0.5 β_{opt}	~2	330
Medium β	570	704.42	36 (4/CM)	0.67	~2	870
High β	2000	704.42	84 (4/CM)	0.86	~2	1100
HEBT	2000	–	0	–	~300	–

Site construction work Aug-Dec 2015

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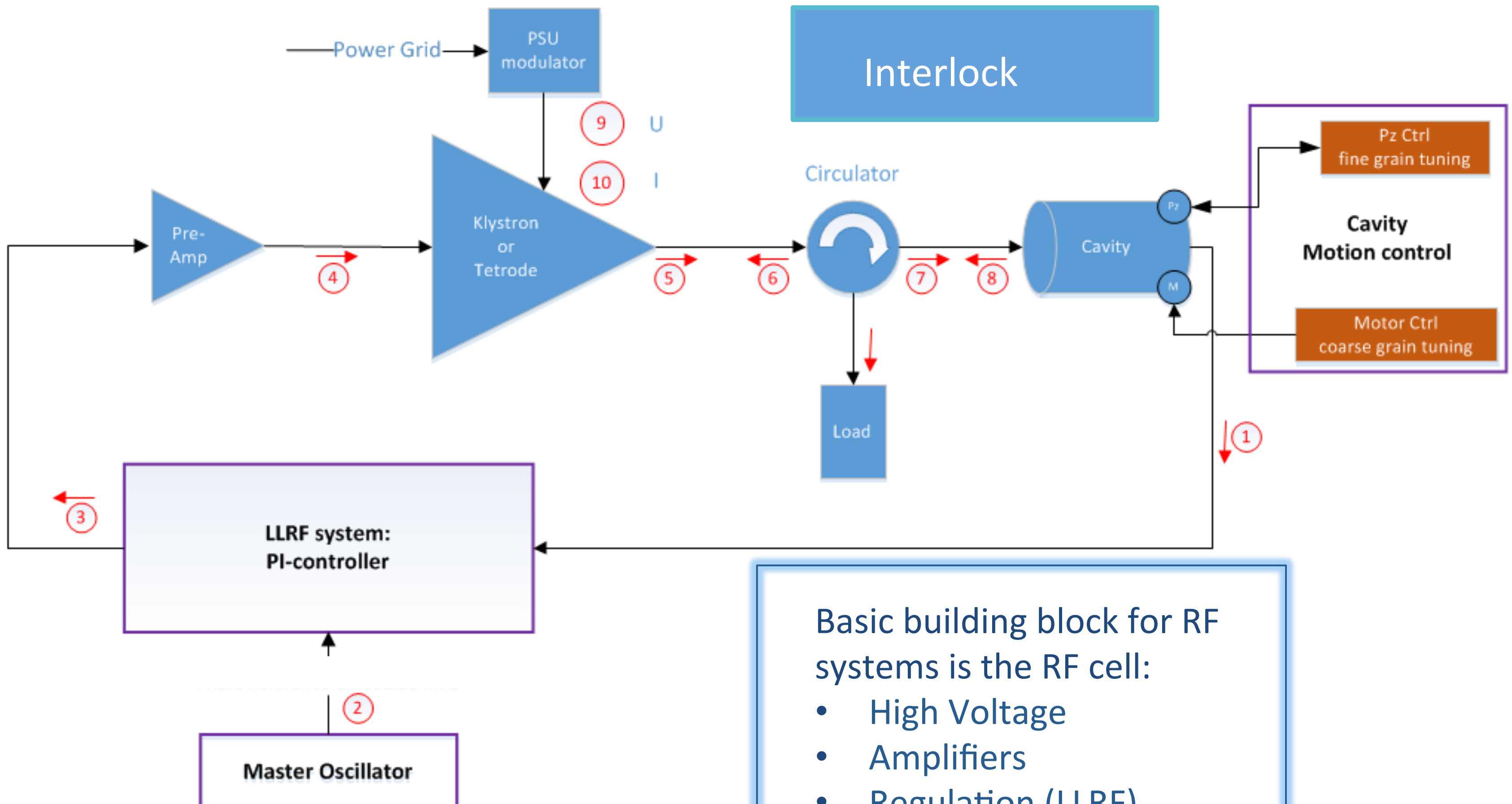
RF systems

- Power to 155 cavities, one RF station/cavity
  - High Voltage new development: SML modulator topology
  - High Power RF Amplifier new development: MB-IOT amplifier (targeted for high beta)
- A large part of the RF systems is provided in collaboration with partners
    - RF NC linac (Spain)
    - Spoke RF stations (Italy)
    - LLRF (Spain and Poland)
    - RF high power distribution (UK)
    - Phase ref distribution (Poland)
    - Installation (Poland))
- Collaboration Lund Univ Uppsala Univ(FREIA facility)

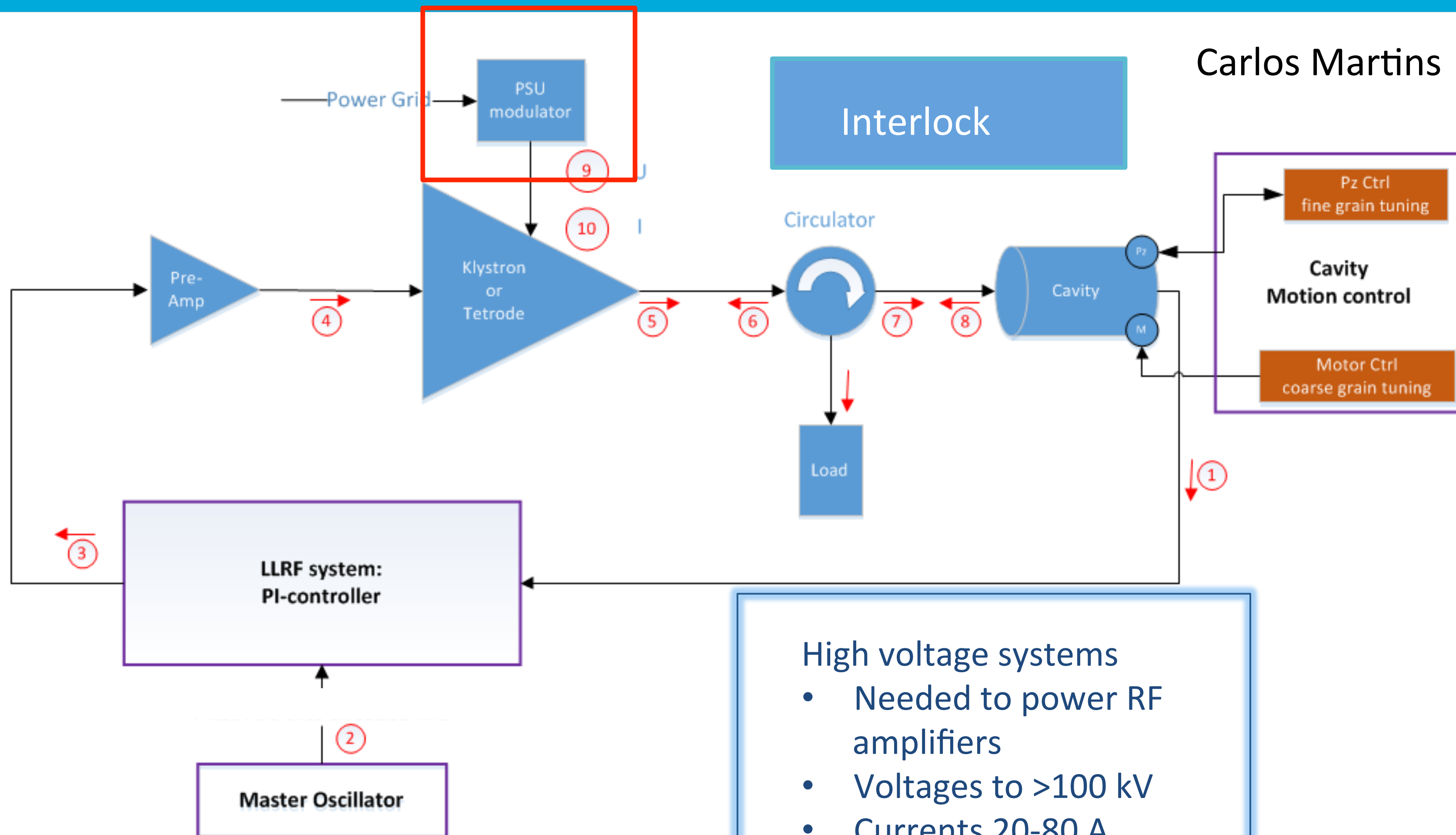
RF Cell



Basic building block for RF systems is the RF cell:

- High Voltage
- Amplifiers
- Regulation (LLRF)
- Protection – Interlock
- Waveguides

High voltage



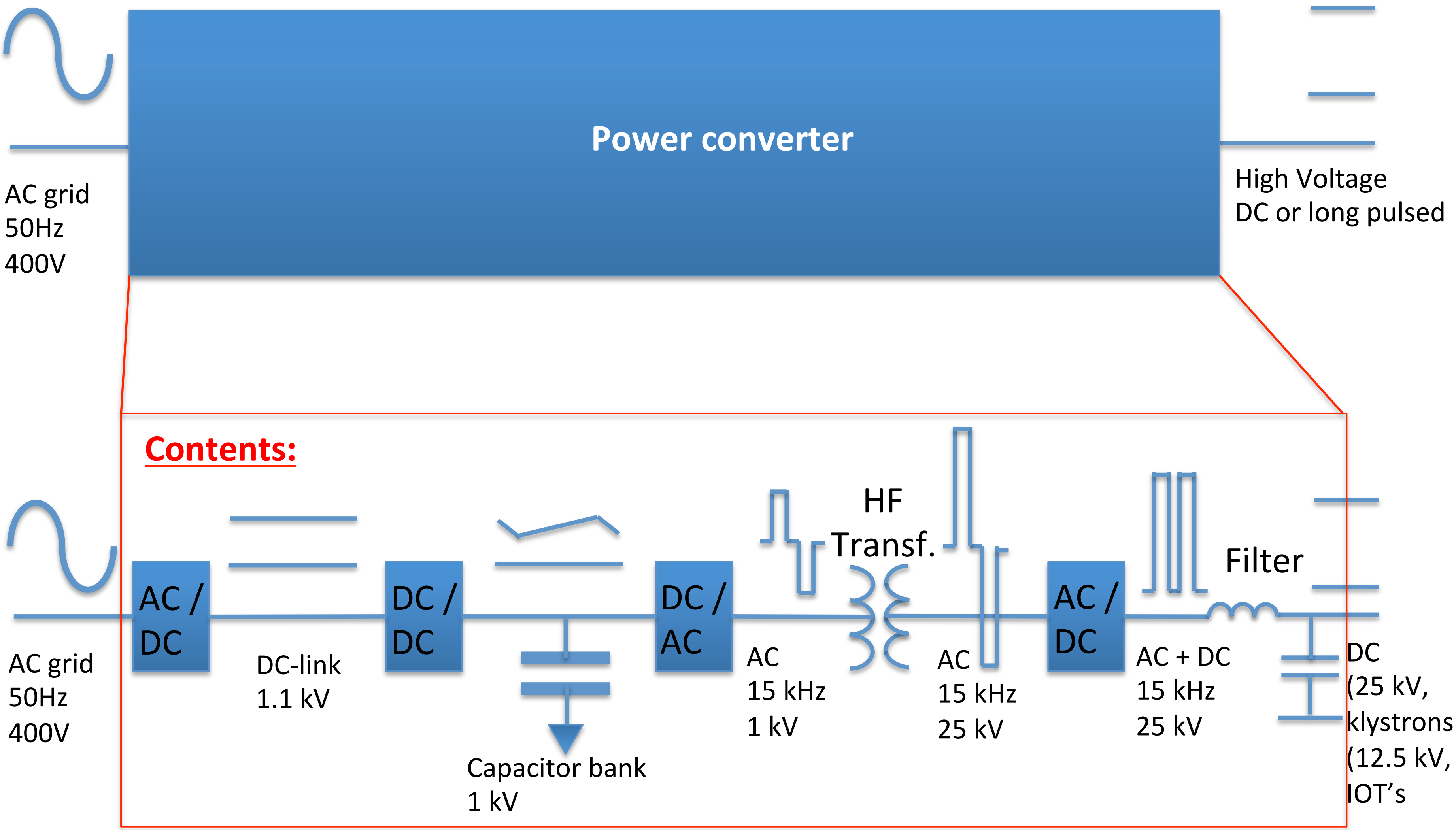
Carlos Martins

High voltage systems

- Needed to power RF amplifiers
- Voltages to >100 kV
- Currents 20-80 A
- Pulsed or cw
- Large and $$$

See lecture
Carlos Martins

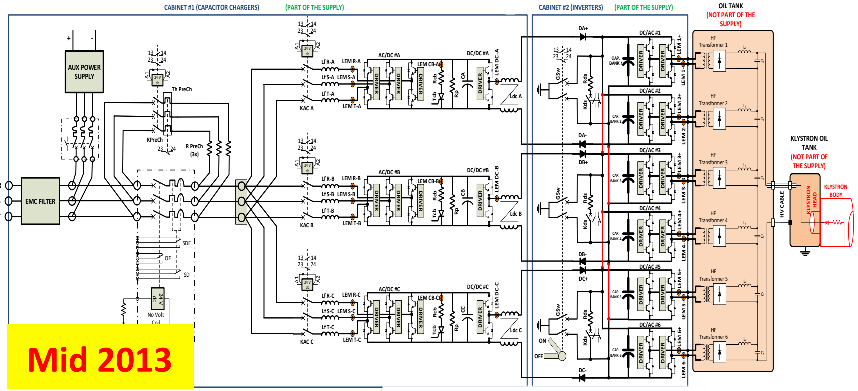
High voltage



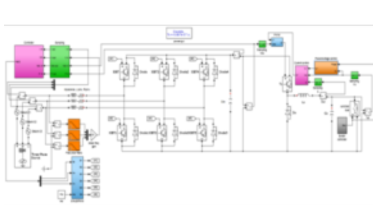
The Stacked Multi-Level (SML) modulator:

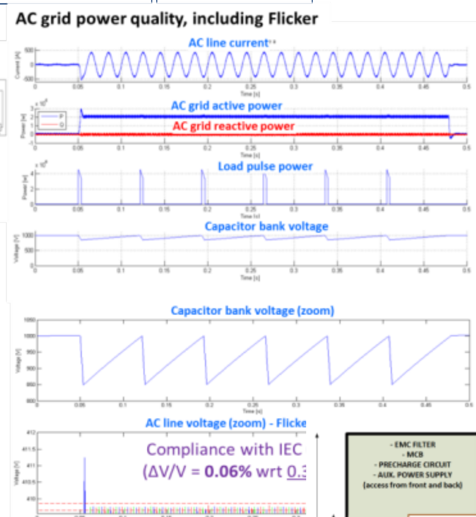
– Development roadmap

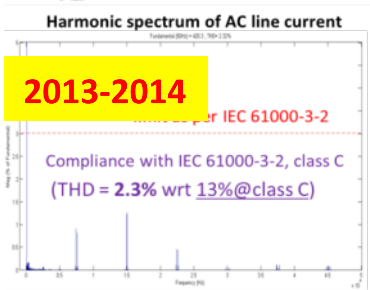
Construction and testing of High Voltage Oil tank assembly Q1 2016



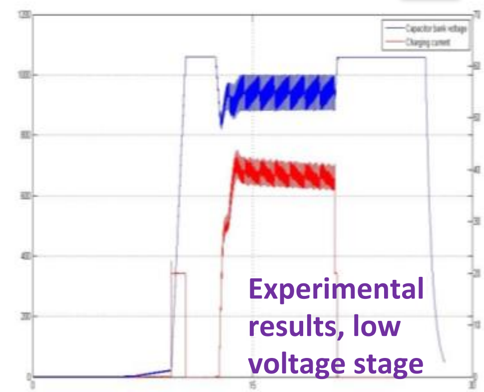
Mid 2013



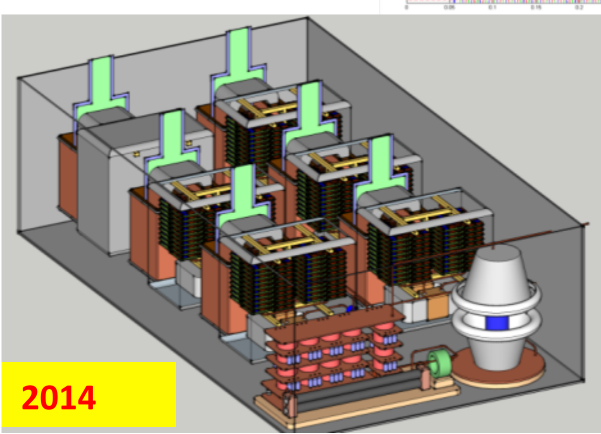




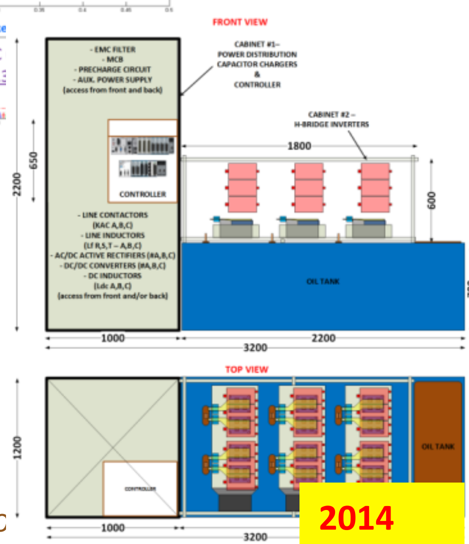
2013-2014



2015



2014



2014

2014

Development strategy ESS

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<table>
<tr><th>Strategy</th><th>Rated power</th><th>Ready/ Delivery</th><th>Validated</th><th>Decision point</th><th>Outcome</th></tr>
<tr><td>A – SML
(ESS internal development)</td><td>660 kVA
(4 klystrons 704 MHz in parallel)</td><td>Dec 2015</td><td>Q1 2016</td><td rowspan="3">If A:
SML fully validated, Q1 2016

If B:
Sept 2016</td><td>Strategy A: Launch call for tender for 660 kVA modulators:
3 units for RFQ/DTL
9 units for medium beta</td></tr>
<tr><td>B:1-Ampegon
(ESS contract)</td><td>330 kVA
(2 klystrons 704 MHz in parallel)</td><td>May 2016</td><td>Fall 2016</td><td rowspan="2">Strategy B: Launch call for tender for 330 kVA modulators:
6 units for RFQ/DTL
18 units for medium beta</td></tr>
<tr><td>B:2 -DTI
(partner contract)</td><td>330 kVA
(2 klystrons 704 MHz in parallel)</td><td>Jan 2016</td><td>Mid 2016</td></tr>
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High power amplifiers

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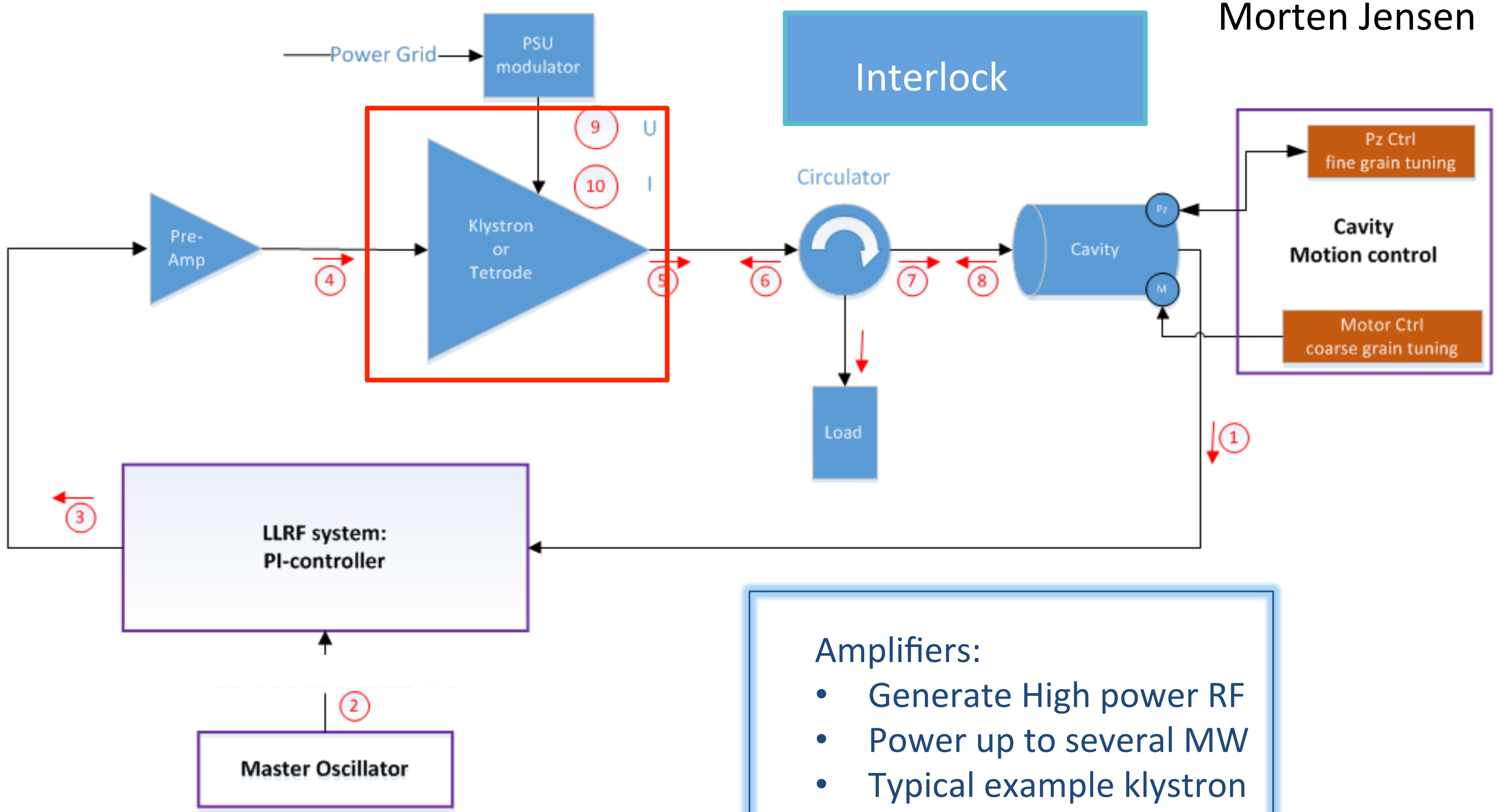
Morten Jensen



Amplifiers:

- Generate High power RF
- Power up to several MW
- Typical example klystron
- Large, $$$

See lecture Morten Jensen

Amplifiers

- Solide state amplifiers
  - Transistors
  - Low voltage
  - Combine many
- Tube amplifiers
  - Vacuum tubes
  - Electron beam
  - High voltage (10 kV-120 kV)
  - Current 5 A-100 A

Solid state power amplifiers

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- Split input in several
- Amplify each separately
- Combine to one output
- Can reach several 100 kW's

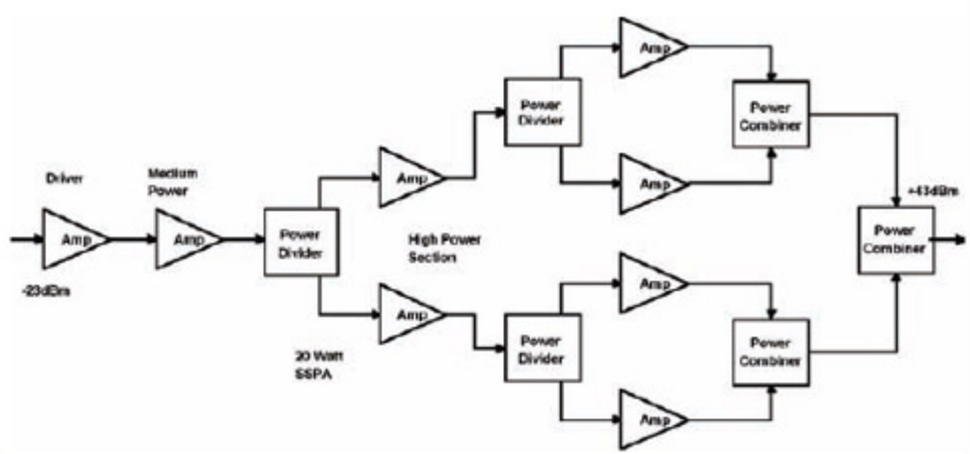
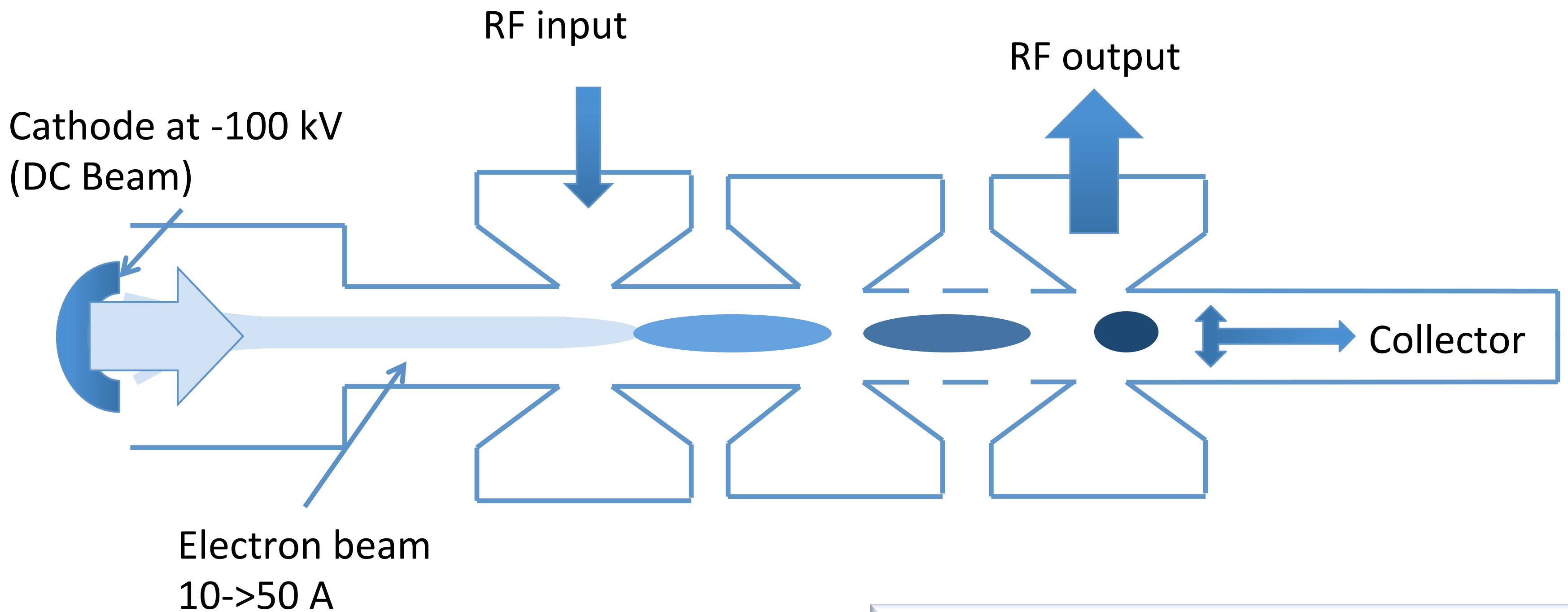


Figure 2: A typical solid state amplifier configuration

Klystron (Velocity Modulated)



Invented in the 1930's
Radar/broadcast applications

- Klystron draws continuous current
  - **Cathode pulsed**
- Klystron is velocity modulated

Other tube types exist
See lecture by Morten Jensen

High power amplifiers ESS linac

Section	Power /kW	Baseline design	Status
Normal conducting RFQ and DTL	2800	Klystron	In kind
Normal conducting bunchers	30	Solid State	In kind
Spoke linac	400	Tetrode	In kind, proof of concept UU
Medium beta linac	1500	Klystron	Prototyping
High beta linac	1500/1200 Klystron/IOT	MB-IOT (decision end 2017)	Prototyping

Normal conducting linac

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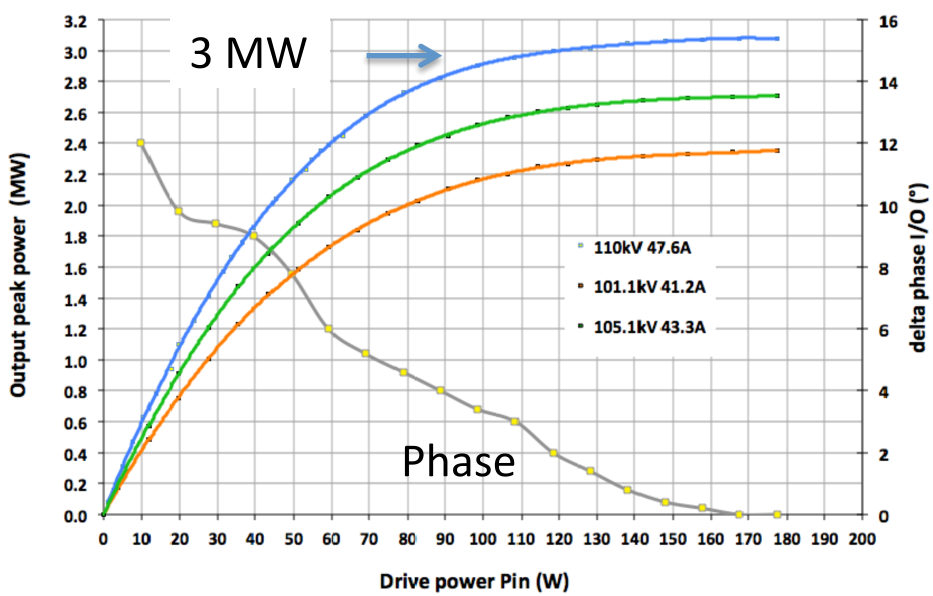
Output vs Voltage



Courtesy of Thales ED

Frequency	352 MHz
RF Power	3 MW peak
High voltage	to 115 kV
Current	to 50 A
Repetition Rate	14 Hz
Pulse width	3.5 ms

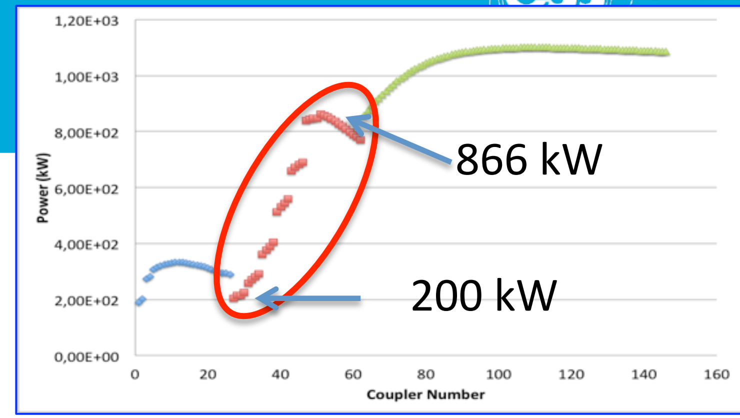
Two klystrons per modulator

Thales TH2179

CPI VKP-8352A

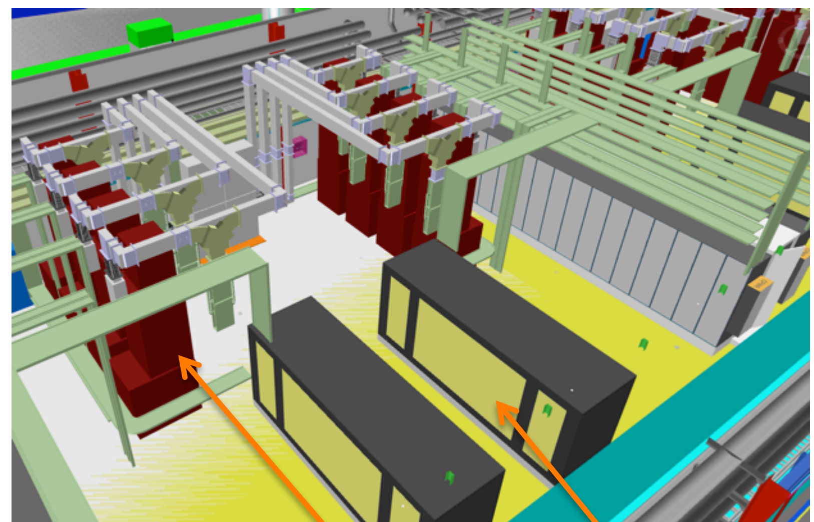
Medium beta linac

Frequency	704 MHz
Power	1.5 MW peak
High voltage	to 115 kV
Current	To 25 A
Repetition Rate	14 Hz
Pulse width	3.5 ms



High Power Density: 12 MW of RF in approx. 10 x 13 m

Vertical orientation to fit in the gallery



Four klystrons per modulator

- **Three prototypes on order:** Thales, Toshiba and CPI
- Design reviews complete
- Delivery expected in **March** (Thales), **May** (Toshiba) and **July** (CPI) 2016

Courtesy of Chiara Marrelli

704 MHz klystron prototypes

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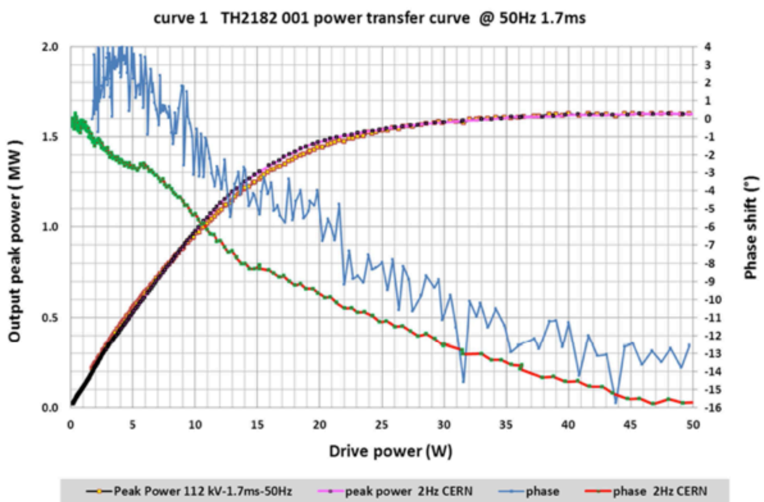
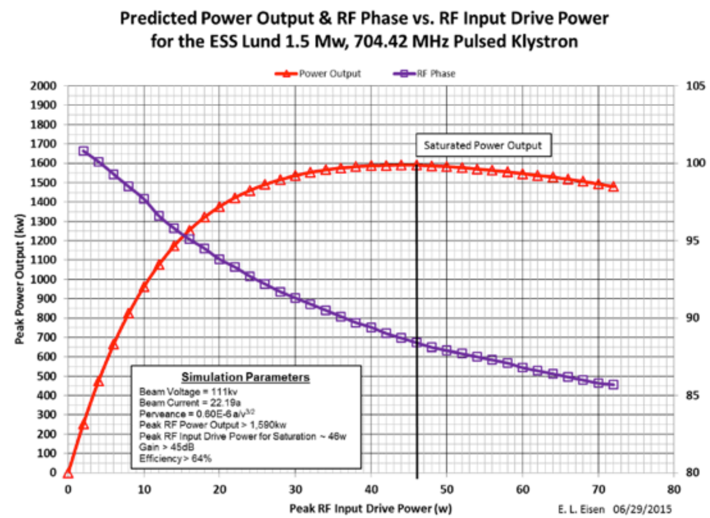
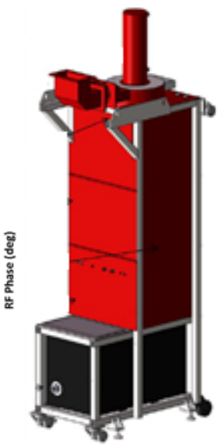
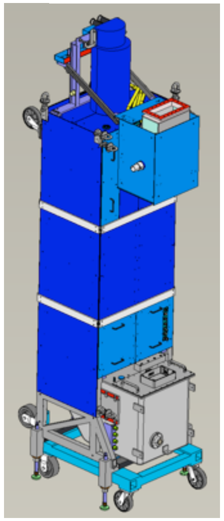
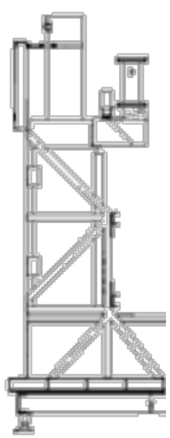


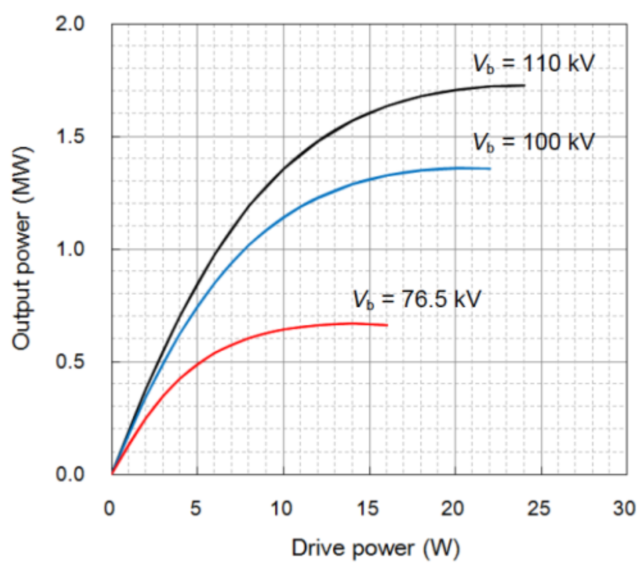






TH2180





CPI VKP-8292A

Toshiba klystron has higher gain

Toshiba E37504

Courtesy of Chiara Marrelli

High Beta linac: Multi-Beam IOTs

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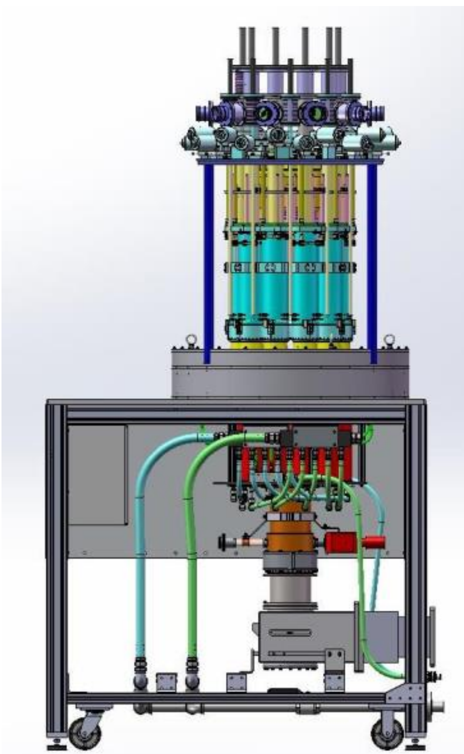
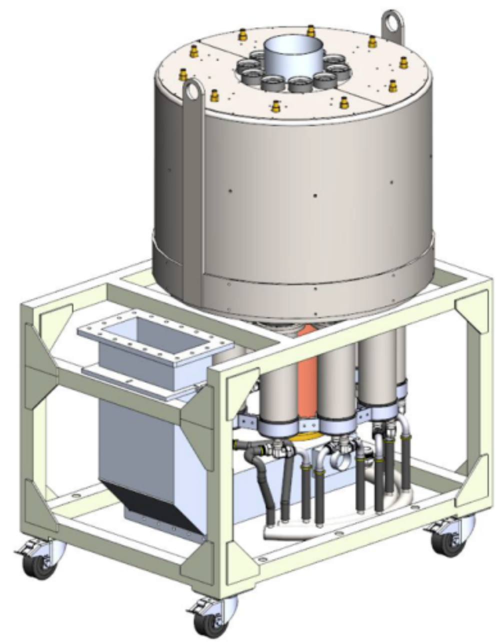


New class of device

- More compact than klystron
- Does not saturate
- Two prototypes on order for Delivery during 2016
- 1.2 MW, 704 MHz

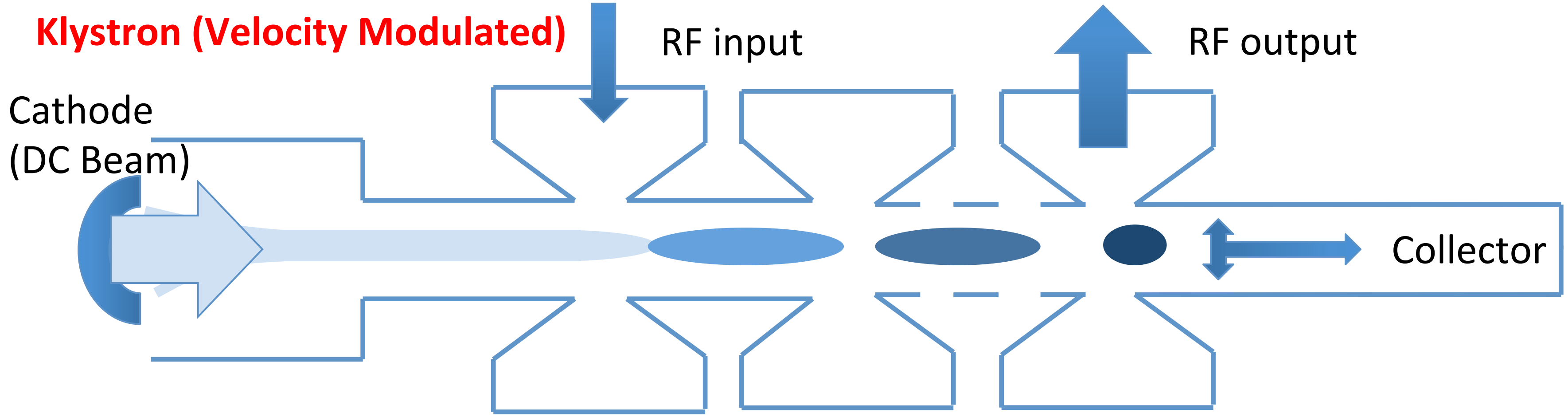


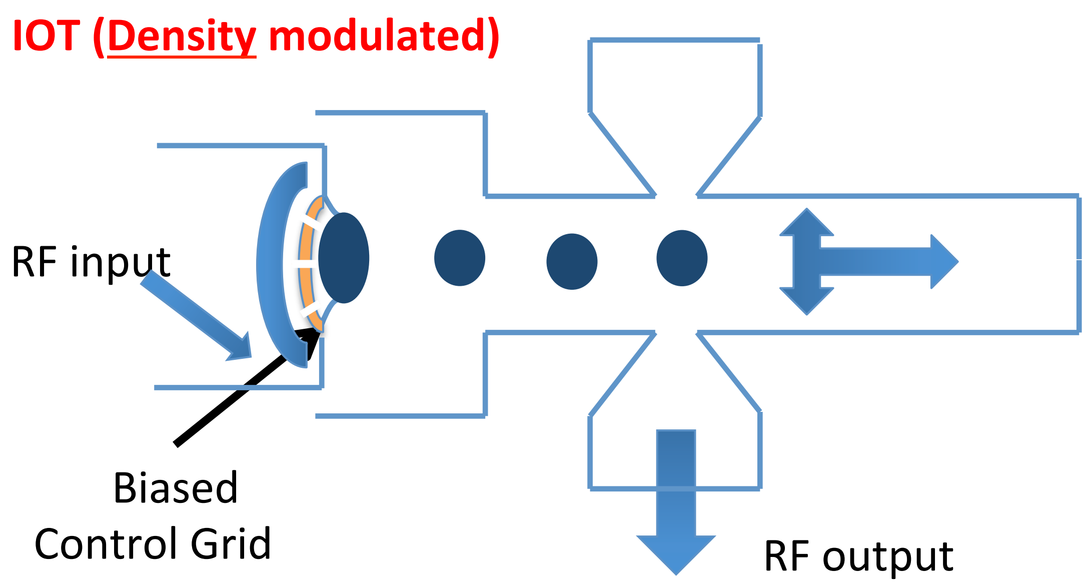
THALES

CPI
Communications & Power Industries
microwave power products division

L3 communications

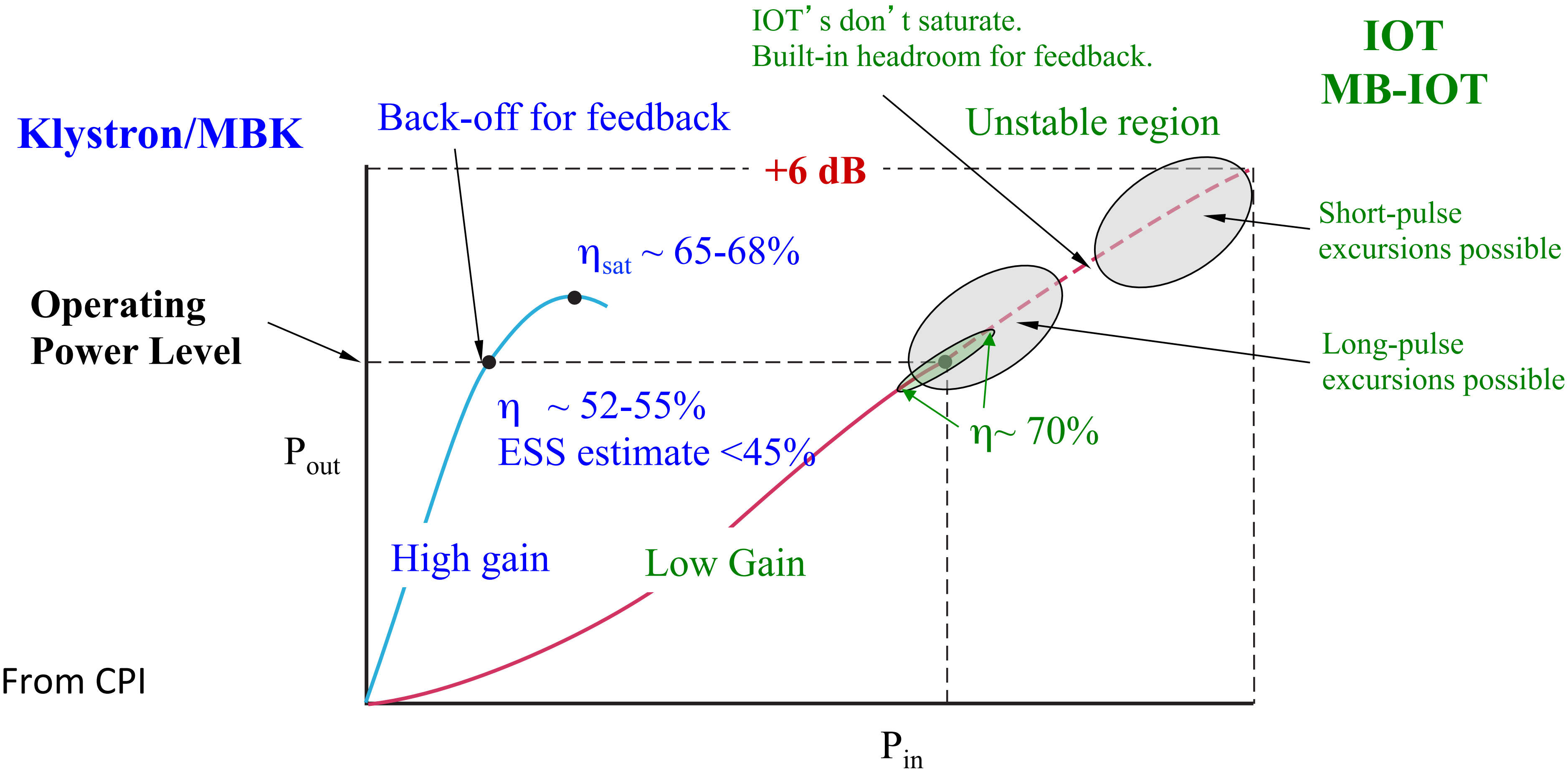
Klystron vs IOT





- Klystron draws continuous current
  - ➢ **Cathode pulsed**
- Klystron is velocity modulated
- IOT has reduced velocity spread
- IOT does not conduct in the absence of input drive

Power transfer IOT vs klystron



From CPI

*** Klystrons: Back-off for feedback cost 30% ***

*** IOTs: Operate close to max efficiency***

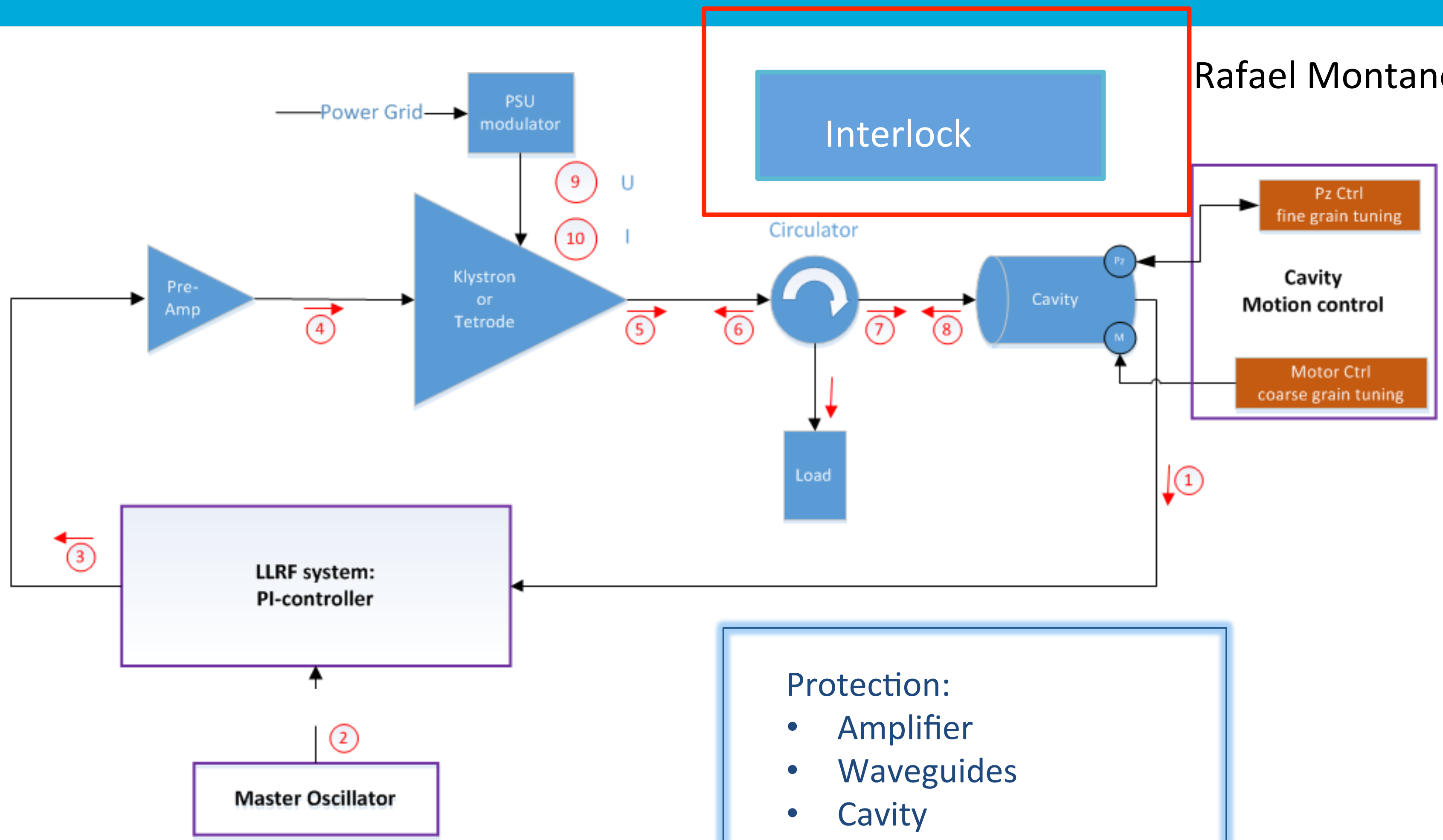
Specification

Parameter		Comment
Frequency	**704.42 MHz**	**Bandwidth > +/- 0.5 MHz**
Maximum Power	**1.2 MW**	**Average power during the pulse**
RF Pulse length	Up to 3.5 ms	Beam pulse 2.86 ms
Duty factor	Up to 5%	Pulse rep. frequency fixed to 14 Hz
Efficiency	Target > 65%	
High Voltage	Low	< 50 kV
Design Lifetime	> 50,000 hrs	

Target: Approval for ESS series production in 2017/18

Interlock

Rafael Montano



Protection:

- Amplifier
- Waveguides
- Cavity
- LLRF
- Fast (μs) and slow (ms)

Local Protection System - Interlocks

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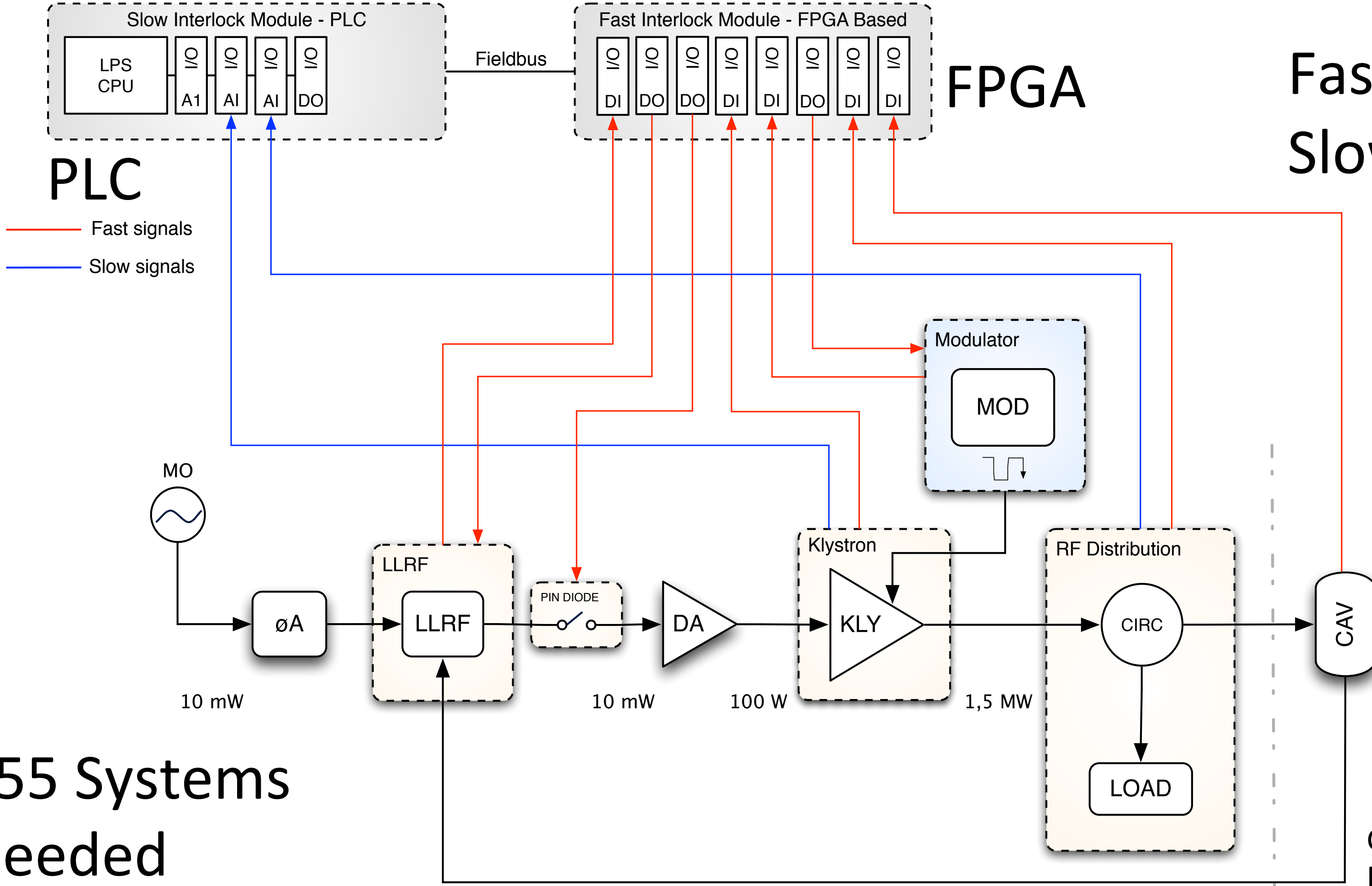
Typical RF Chain separating fast and slow interlocks



FPGA

PLC

Fast – FPGA

Slow - PLC

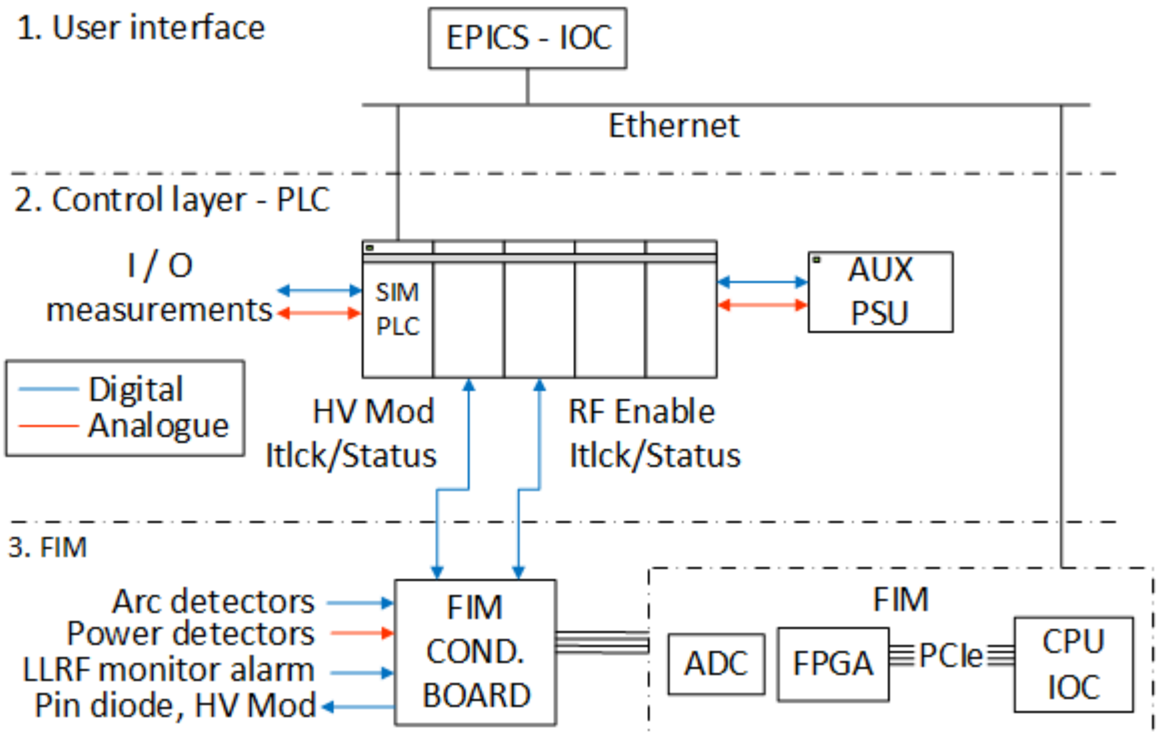
155 Systems Needed

Courtesy of Rafael Montano

RF-LPS UI


RF Local protection system
Device Prefix
RFLPS:
RFLPS:
CPU
Connection Status
Connected
Machine Status
Status word
RF Enable
HV Enable
Standby
ELMG Current ...
Heater Supply ...
Amplifier Off
Reset
Latch mode
Interlock/Alarm
Warning
Read param
Refesh param
Operation Mode
Normal
Normal
Analog signals
Connection Status
COLLINTP
COLLINTP
Connected
Status
Device type
1
Conversion Type
0
Error code
0
Time of last interlock
2015-10-28 11:23:19.28-11
Value
Engineering units
23.18
Raw
2318
Status Word
Warning
Interlock/Alarm
Disable (Internal)
Force
Can't Force
Never Latch
IsFirst
Low Alarm
High Alarm
Settings
HIHI alarm limit
22.00
22.00
HIGH alarm limit
21.50
21.50
LOW alarm limit
20.00
20.00
LOLO alarm limit
19.00
19.00
Adjustment offset
0.00
0.00
Simulated value
0.00
0.00
23.24
22.5
22
21.5
20.73
Digital signals
Connection Status
SOLPSU02ITLCK
SOLPSU02ITLCK
Connected
Status
Device type
4
Error code
0
Time of last interlock
2015-10-28 11:22:52.198
Value
Signal
False
Raw
False
Status word
Bool value
Interlock/Alarm
Force to
Disable (Internal)
Force
Can't Force
Never Latch
IsFirst
InvertDO
Settings
Hold high
0
0
Simulated value
False
False

ESS RF-LPS HW Configuration



Klystron protective interlocks

Intermediate protection – The Klystron beam voltage must be interrupted within 100 ms, of following conditions:

- Solenoid voltage
- Solenoid current
- Ion-pump current
- Collector flow rate
- Body flow rate
- Window air flow rate

RF Drive Interruption – The RF Drive must be removed within 10 μs under any of the conditions listed below:

- Arc detectors
- Reflecting power

Filament interruption – In order to protect the filament from poor vacuum conditions, a protective circuit shall switch off the filament.

RF-LPS prototype design – signal types

The PLC shall collect and process more than 70 signals per station according to the preliminary signal list requirements

- Temperature
- Cooling flow-rates
- Cooling water pressure
- Solenoid PS interlock signals
- Vacuum
- Cryomodule system ready

Fast Interlock Module (FIM) more than 20 signals

- Power forward/reflecting
- Arc detectors
- Modulator remote interlocks
- LLRF monitor alarm
- Pin diode

LLRF

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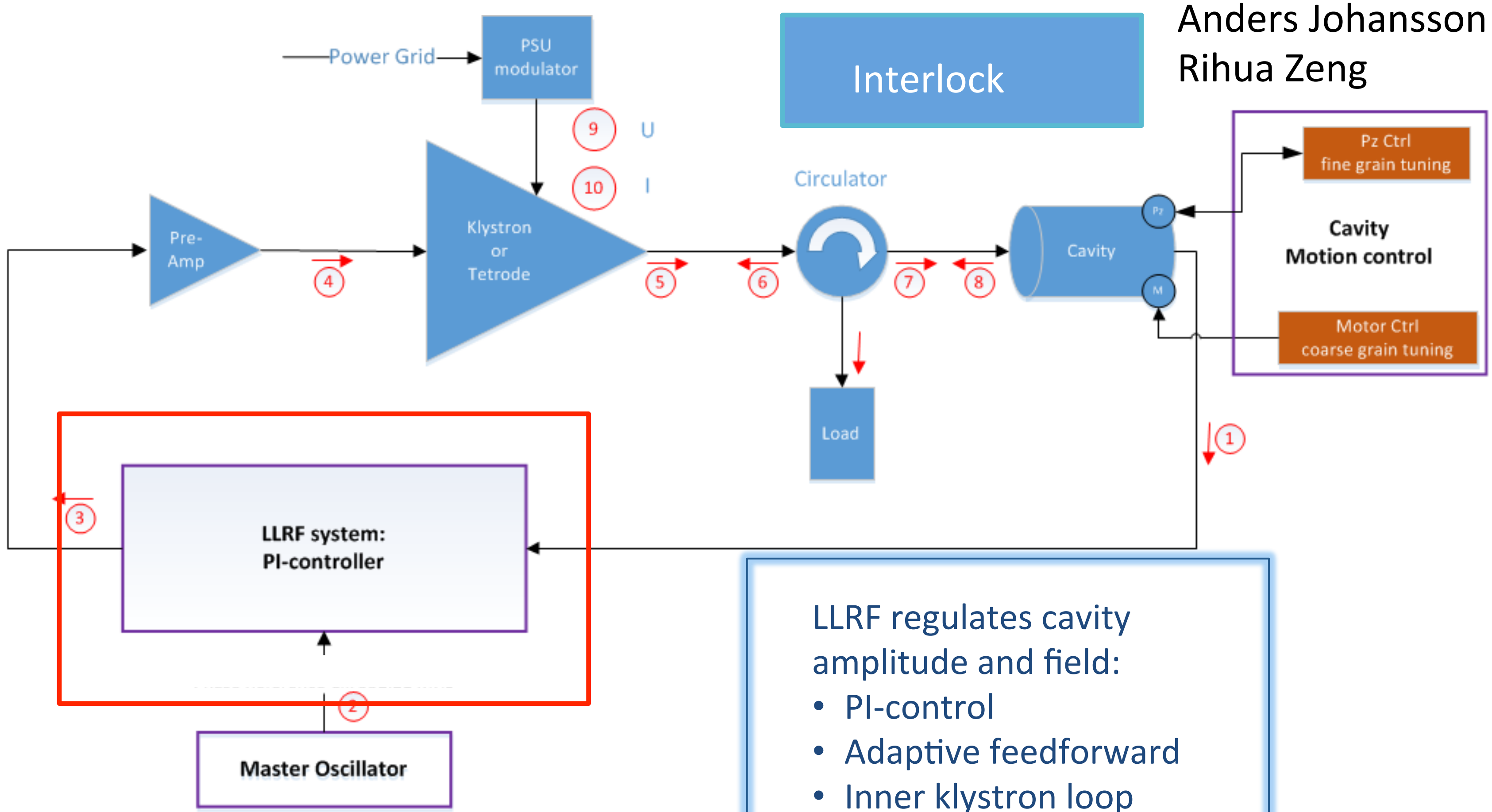
Anders Johansson LU
Rihua Zeng

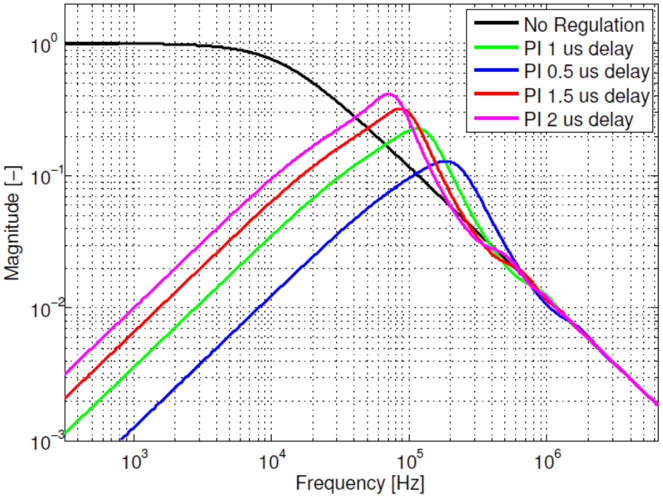


LLRF regulates cavity amplitude and field:

- PI-control
- Adaptive feedforward
- Inner klystron loop
- Beam current variation compensation

ESS LLRF prototype and efforts

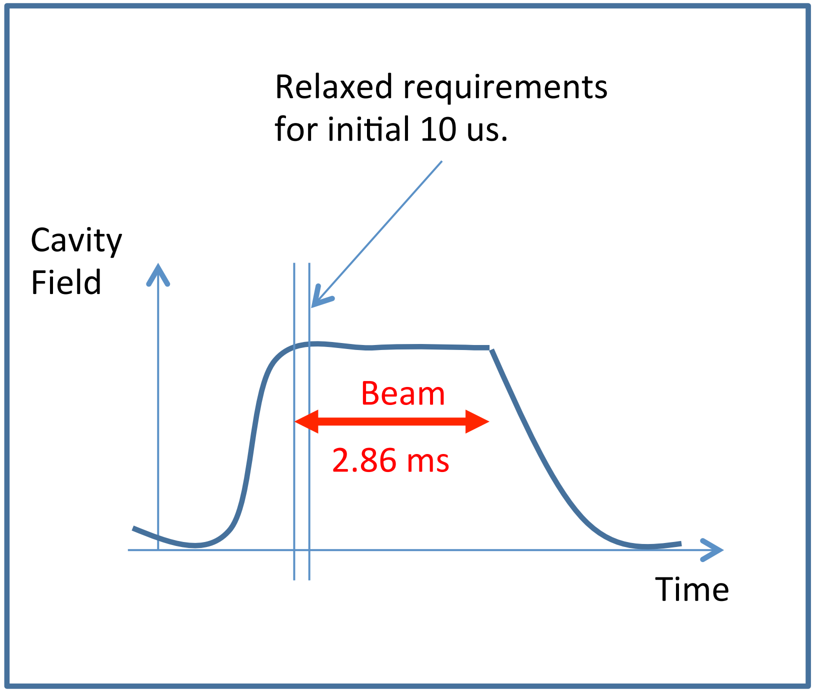
- μTCA 4 standard
- 352 and 704 tested and running
- Adaptive feedforward learning
- Lorentz force detuning compensation
- Tests (352 @ FREIA, 704 @ Saclay)
- Klystron linearization
- Requirements on precision
  - Control/cavity system modeling
  - Beam physics (loss) modeling
  - Regulation system set-up
  - Handling beam current variations
  - Handling modulator ripple



Field Stability

Current requirements for regulation accuracy of the cavity field.

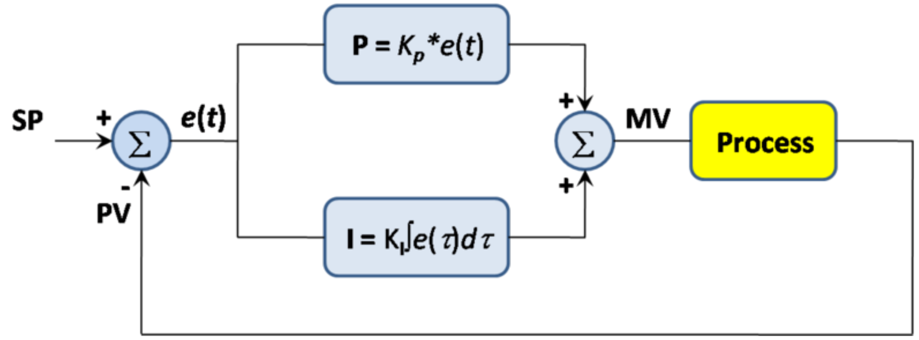
- RFQ
  - +/- 0.2 % RMS amplitude
  - +/- 0.2 º RMS*
- Normal Conducting
  - +/- 0.2 % RMS amplitude
  - +/- 0.2 º RMS
- Super Conducting
  - +/- 0.1 % RMS amplitude
  - +/- 0.1 º RMS



*Relative the phase reference line. All other phase requirements relative the beam.

PI-control

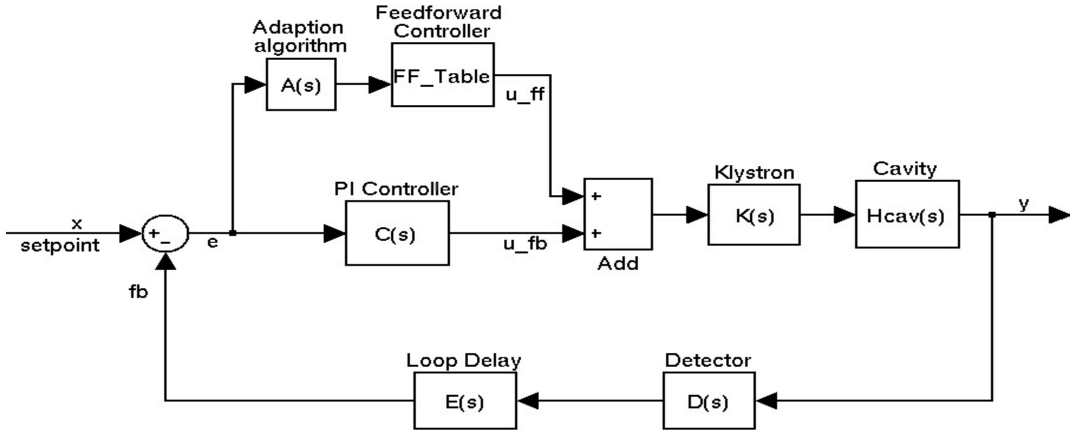
- Classic controller
  - Proportional
  - Integral



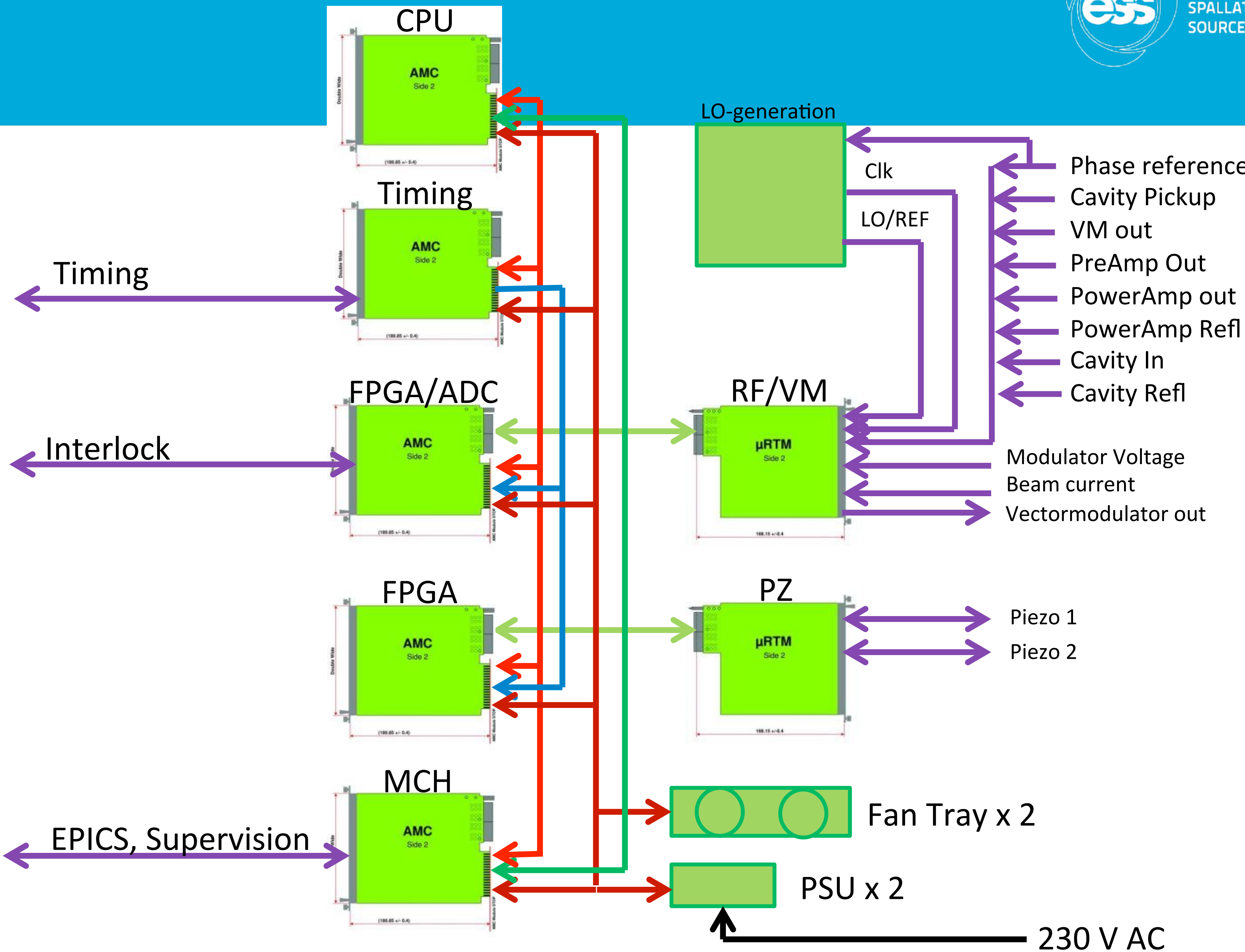
- Two independent, but equal, PI-controllers, on I and Q.
- An additional inner loop for linearization is planned.

FeedForward control

- Based on stationarity of system
  - Every pulse looks the same
  - Adaptation handles slow drift



704.42 MHz Medium-β MTCA.4 LLRF



Master oscillator, phase reference line

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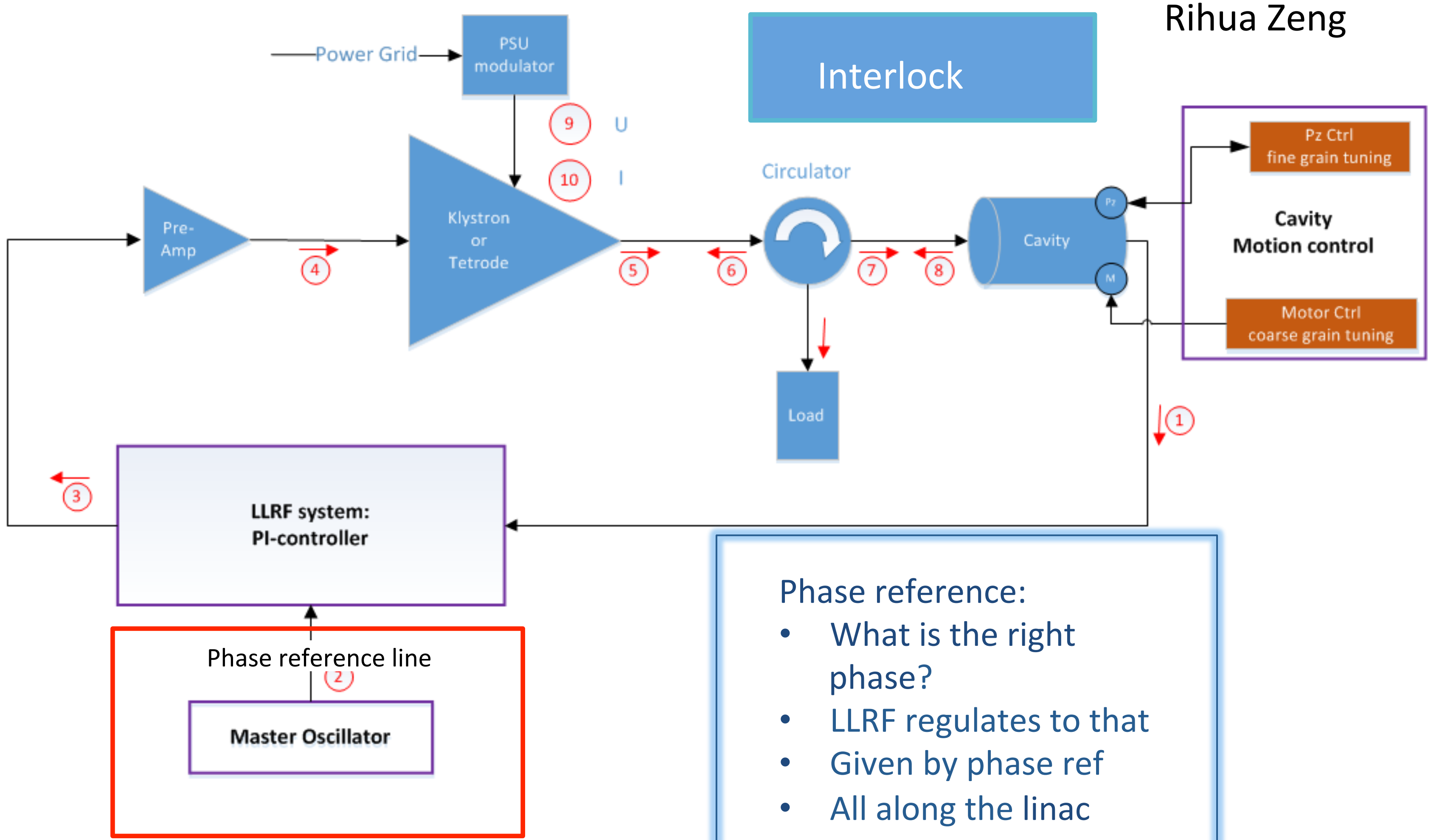
Rihua Zeng

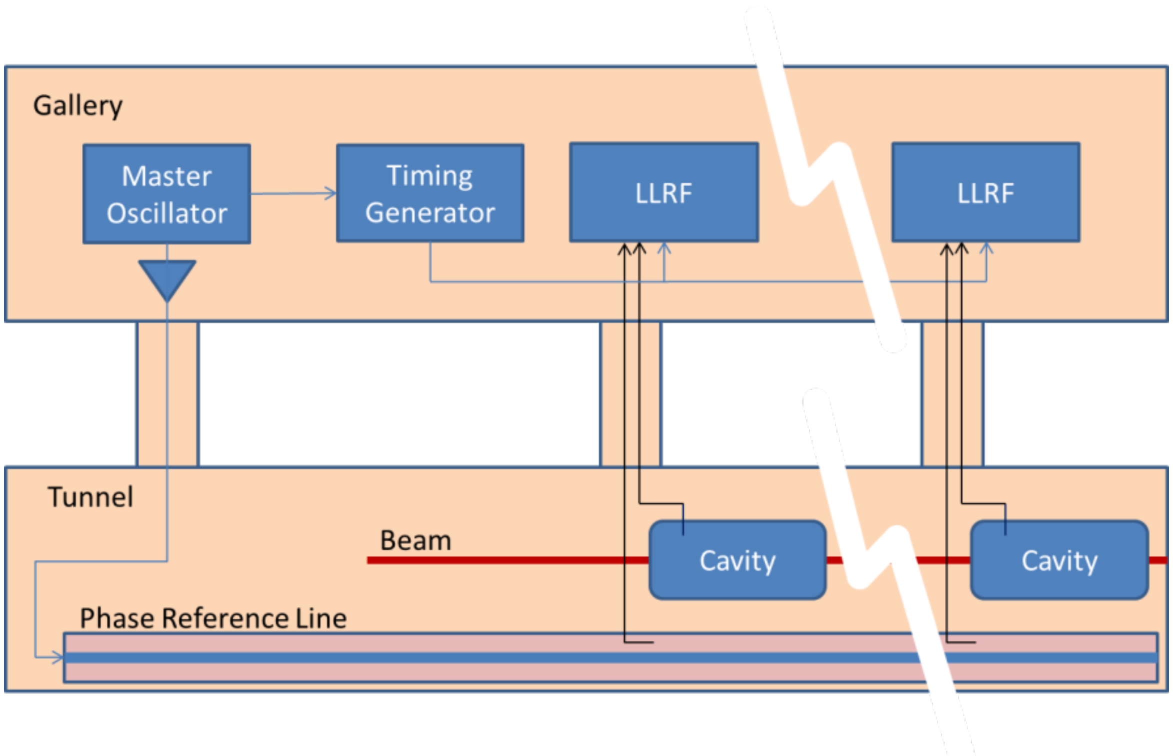


Phase reference:

- What is the right phase?
- LLRF regulates to that
- Given by phase ref
- All along the linac

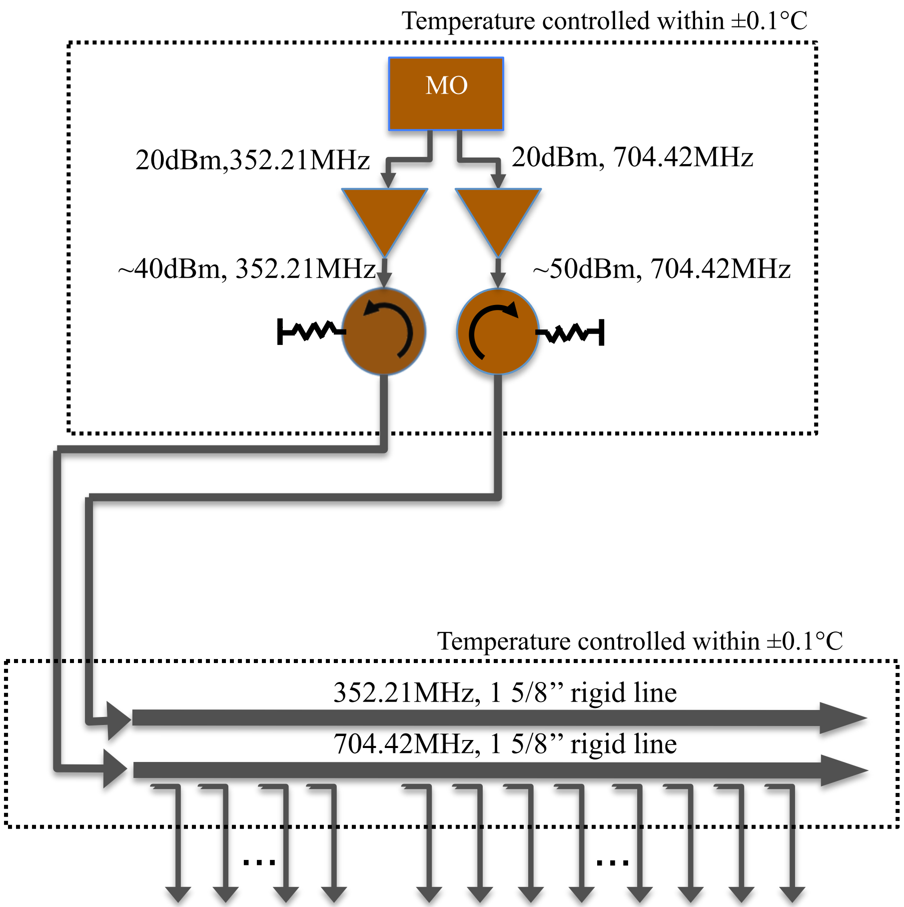
Timing and Phase Reference

- Phase reference line in tunnel.



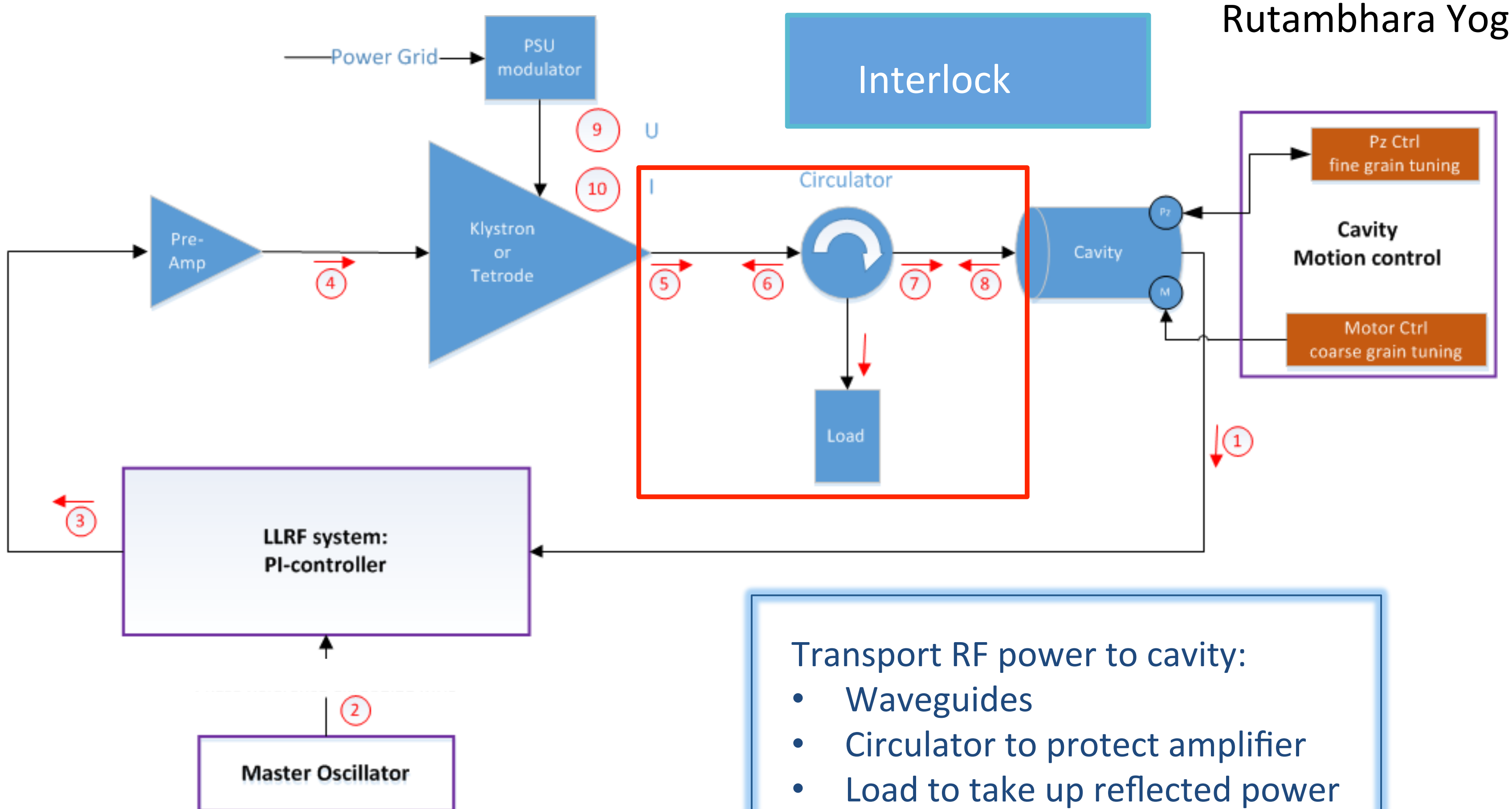
Phase ref line

- First design prepared
- Prototyping 2015-2016, scaled down version to test
    - Phase reference signal delivery system
    - Air pressure system
    - Temperature control system
    - Data acquisition, drift calibration, EPICS interface
- Several design alternatives



Distribution system

Rutambhara Yogi

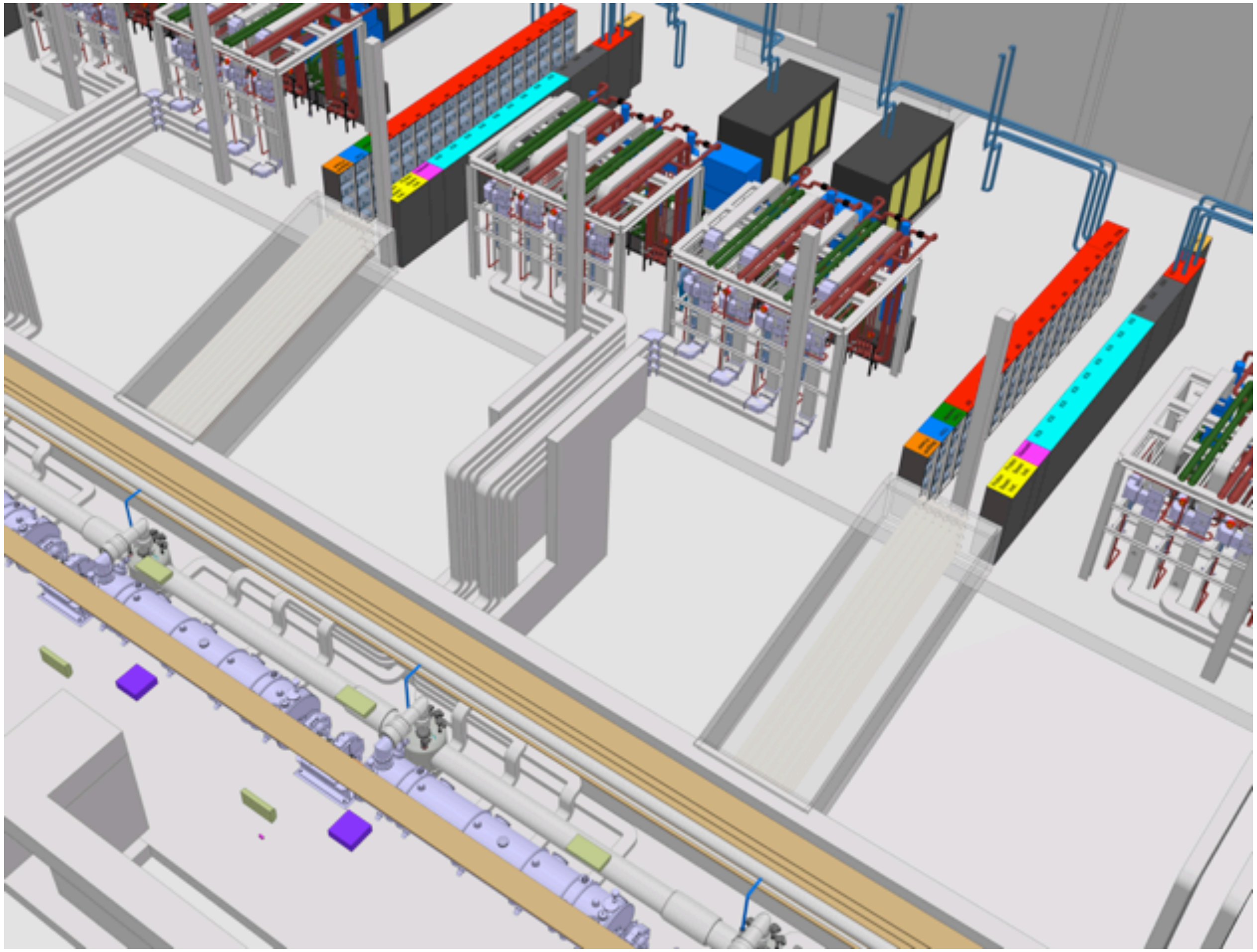


Transport RF power to cavity:

- Waveguides
- Circulator to protect amplifier
- Load to take up reflected power
- Couplers for measurement
- Arc detectors for protection

RF distribution transports RF power

- Waveguides, circulators, loads, directional couplers

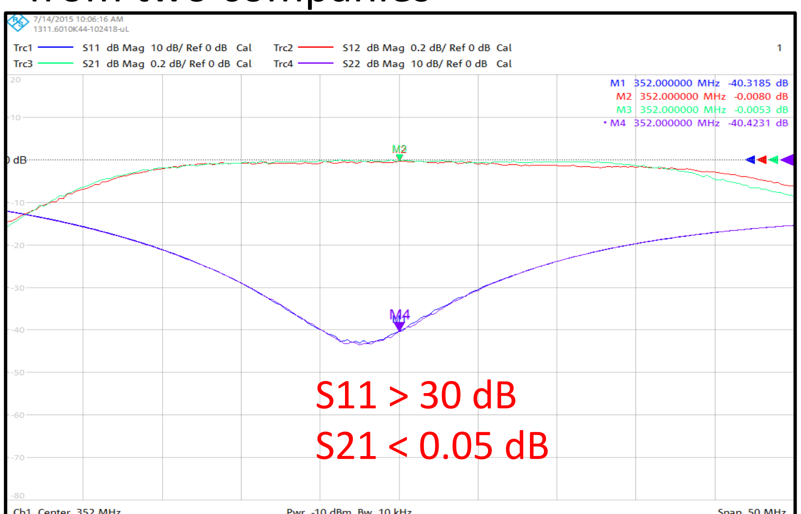


Distribution: Waveguide, coax, circulators and RF loads

ESS needs several kilometers of waveguide and thousands of elbows

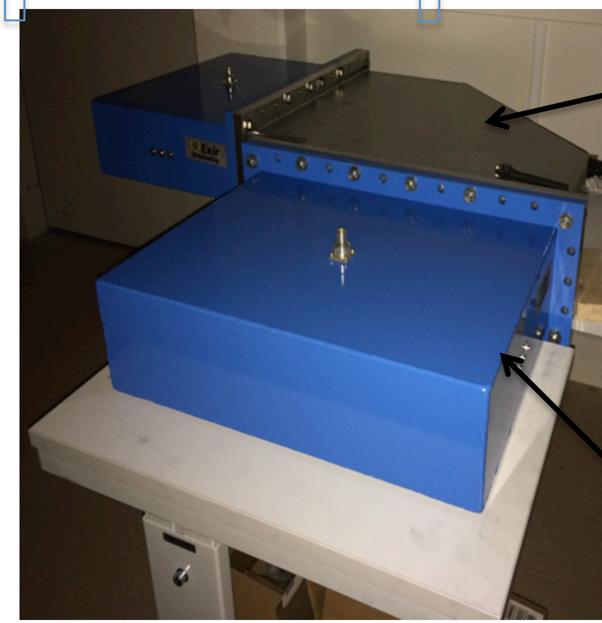
- Simple to design
- Detailed manufacturing drawings allow manufacture by variety of companies
- Potential of significant cost saving

First waveguide prototypes received from two companies



ESS Design

- Waveguide extends through flanges



H-Elbow

Coax-waveguide Adapters

- Contracts signed for prototypes for 704 MHz circulators and loads
  - Circulators: AFT, FMT and MEGA
  - Loads: AFT, Thales and MEGA

Courtesy of R Yogi

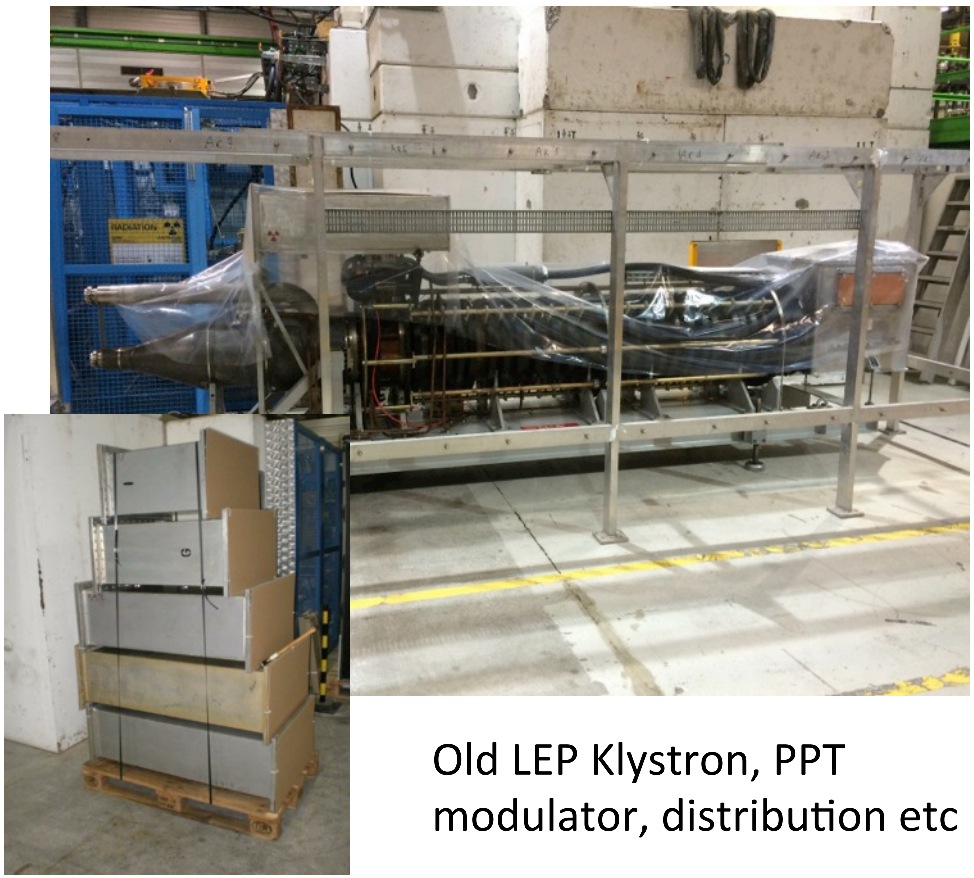
Tests

- It is vitally important to prototype and test RF equipment
- No large facility works without a test stand
- ESS will employ several test stands:
  - Integration test stand in Lund
  - FREIA test stand in Uppsala (352 cryomodules, 352 power)
  - Cryomodule test stand at ESS (704 cryomodules)
  - RF test stand at ESS (all high power RF components)
  - Modulator test and repair lab at ESS facilities
  - CERN tests of IOT

Integration Test Stand

Integration test stand being prepared in M-building, Södra apparathallen

- First setup will be with CERN modulator and klystron
- Spring/summer 2016 test with ESS modulator and klystron prototypes



Old LEP Klystron, PPT modulator, distribution etc

Next Steps

- Prototypes that arrive or are finalised during 2016:
    - Klystron
    - HV modulator
    - IOT
    - Circulator/loads
    - Interlock
    - LLRF
- Tests of equipment in Lund, Uppsala, CERN…
- Follow up and finalization of all in-kind contracts
- ….
- Installation, commissioning
- Starting operation 2019
- Full installation in 2022

Summary

- RF is used to accelerate particles via resonant cavities
- RF systems span many disciplines
  - HV engineering
  - Physics
  - Microwave technology
  - Electronics
  - Automatic control
  - Test and measurements
  - …
- RF is great fun!

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Thank you