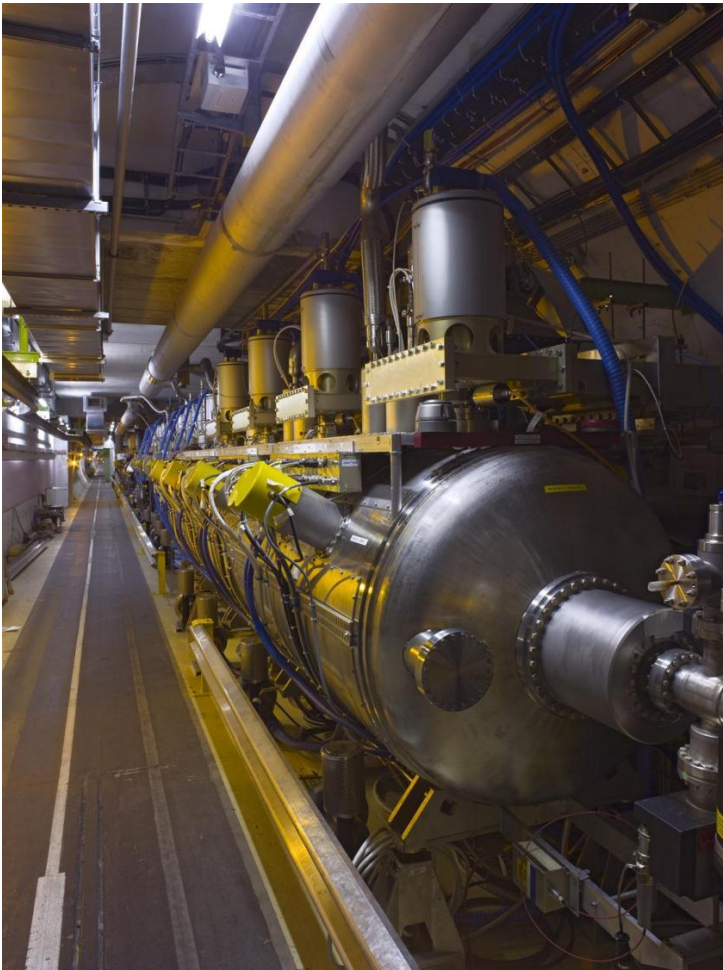


## SC RF Prototype Design and Cryogenics

Edmond Ciapala, Friedrich Haug

Rama Calaga, Erk Jensen

- SC RF and Infrastructure at CERN
- New SCRF projects
- RF & Cryogenics for the LHeC
- Demonstrator for the LHeC ERL
  - Specs, feasibility, goals, infrastructure, location & timeline
- LHeC related SC RF R&D topics
- Conclusions



## Basic parameters:

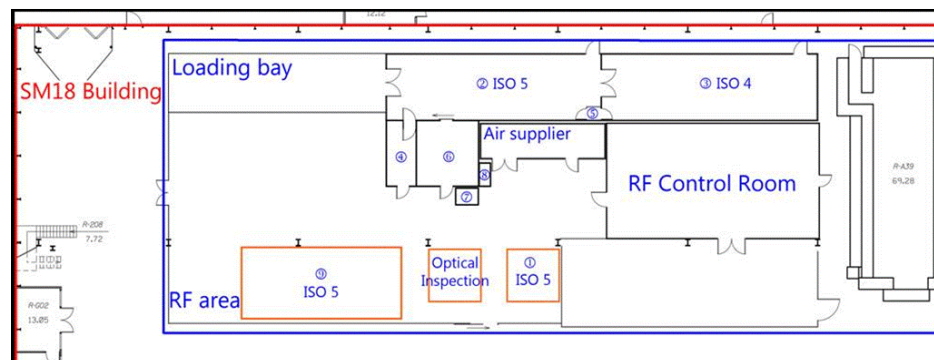
- 8 SC single cell cavities/beam
- Need to handle very high beam currents – LHC  
Nominal beam is 0.56 A d.c.  
- LHC could go up to twice nominal..
- Low R/Q:  $44 \Omega$  (Low Z at high  $Q_{\text{ext}}$ )
- Total 16 cavities , in 4 cryomodules at IR4
- **Technology: Nb sputtered on Copper – as LEP**
- 2 MV nominal per cavity, 5.5 MV/m nominal gradient
- Conditioned to 50 % higher prior to their installation in LHC – Could just reach max. 11 MV/m in test
- Variable power coupler,  $11,000 < Q_{\text{ext}} < 200,000$   
=> High bandwidth at injection for damping of injection transients / higher voltage during physics
- High power handling of coupler ( $> 300\text{kW}$ )
- One klystron per cavity, rating 330 kW

*LHC Cryomodules in RUX45*

- CERN SCRF Installations in SM18 date from 1990s and LEP, with minor refurbishing for the LHC cavities

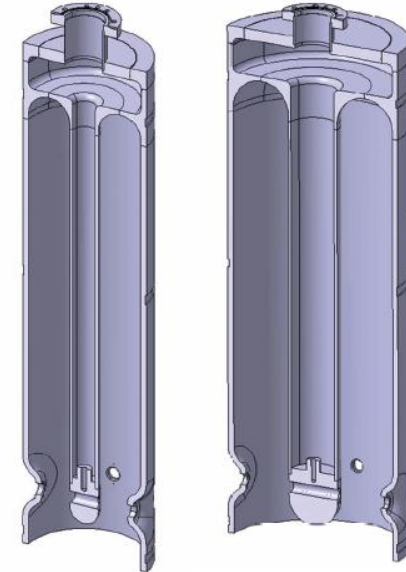
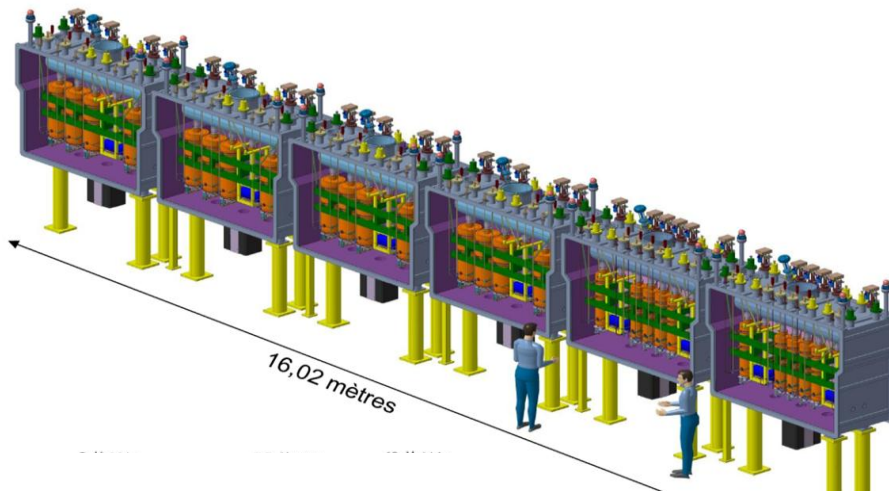


- For new projects, a major upgrade of facilities is in progress to handle modern high gradient, high Q cavities:
  - New HP rinsing equipment & UP water for preparation of cavities and components
  - New clean room
  - Improved cryo, with 2K operation
  - Modern diagnostics equipment
- *Input from other Labs, e.g. DESY, SACLAY, BNL, Fermilab & JLAB gratefully acknowledged*



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- Variable energy between 1.2 and 10 MeV/u
- 32 SC QWR (20 @  $\beta_0=10.3\%$  and 12 @  $\beta_0=6.3\%$ )

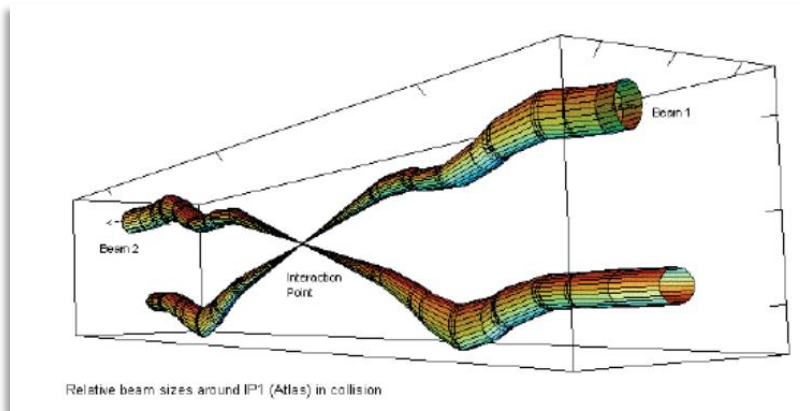


Low  $\beta_0$  QWR (left) and high  $\beta_0$  QWR (right).

- A string of up to 6 cryo-modules:
  - 4 cryo-modules with 5 high-beta cavities + ancillaries each (*first phase*)
  - 2 cryo-modules with 6 low-beta cavities + ancillaries each (*second phase*)
- **Technology is Nb sputtered on Cu**
- First cavities being tested – learning process, collab. with INFN Legnaro

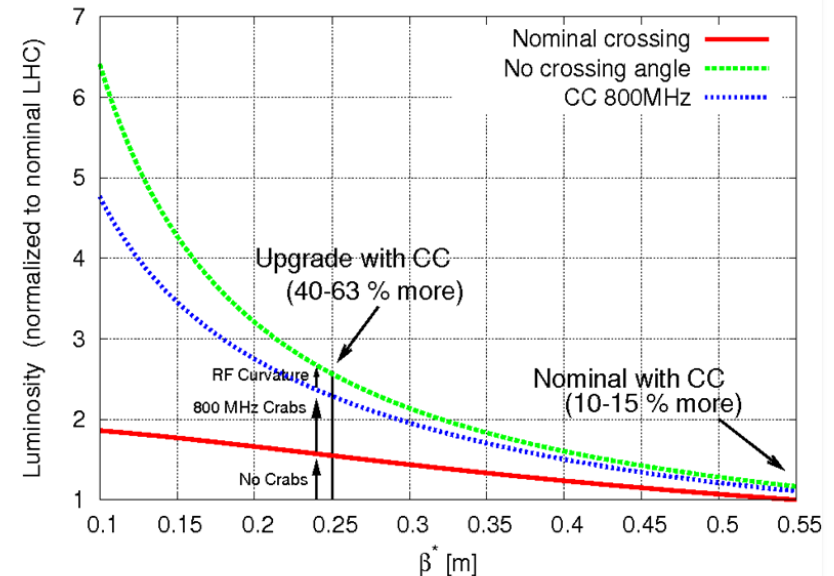


# Deflecting Cavities for LHC – context



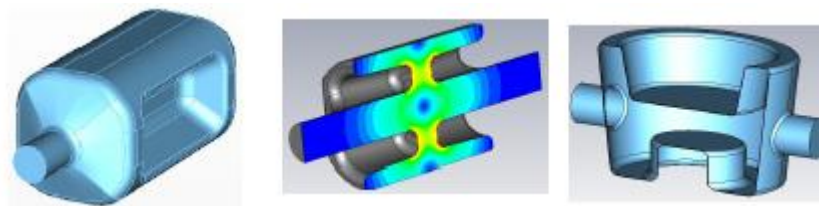
- Crab cavities can compensate for this geometric effect by tilting the bunch giving a luminosity increase of about 50 % at  $\beta^*$  of 25 cm.
- In addition, crab cavities provide an ideal knob for **luminosity levelling**;
- This allows optimizing for **integrated** rather than peak **luminosity**!

- Many bunches closely spaced requires **non-zero crossing angle** to avoid parasitic collisions and to reduce beam-beam effects;
- With non-zero crossing angle, luminosity gain by squeezing beams further is small (**red curve below**).



# 400 MHz SC compact deflecting cavities

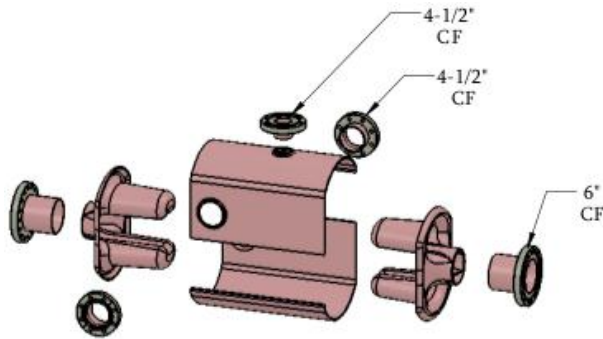
- Novel designs to fit tight space requirements in IR1 and IR5



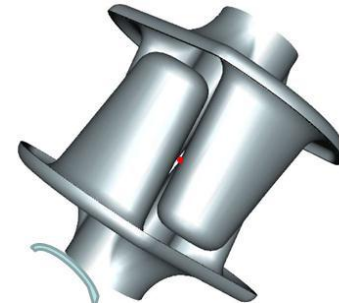
Values for 400 MHz, 3 MV integrated kick	Double ridge (ODU/SLAC)	LHC-4R (ULANC)	¼ Wave (BNL)
Cavity radius [mm]	147.5	143/118	142/122
Cavity length [mm]	597	500	380
Beam Pipe radius [mm]	42	42	42
Peak E-field [MV/m]	33	32	47
Peak B-Field [mT]	56	60.5	71
RT/Q [ $\Omega$ ]	287	915	318
Nearest OOM [MHz]	584	371-378	575

↓ ↓  
Prototypes of these cavities to  
be tested this year

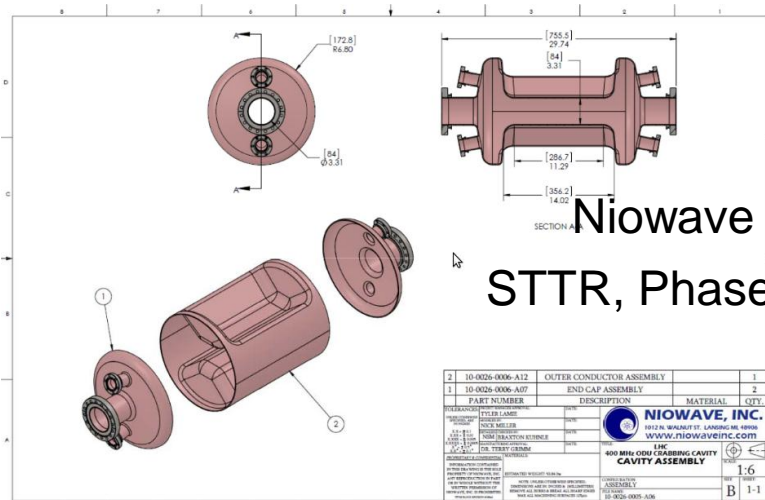




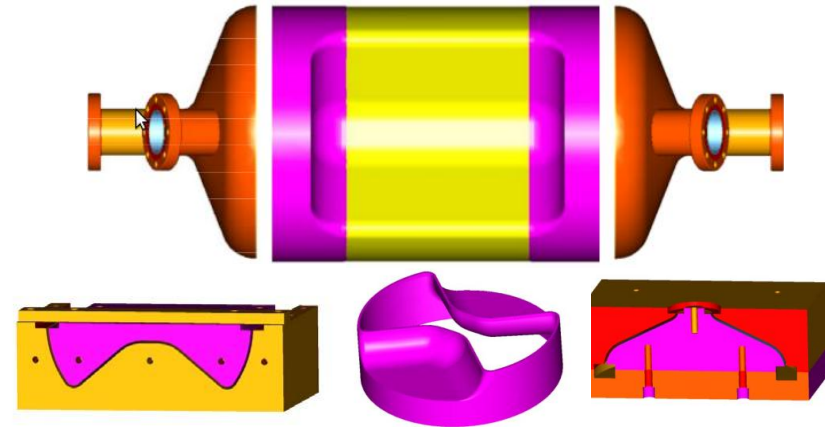
Nb rods from solid Ingot via EDM  
(significant material saving)



Finished cavity at Niowave



Niowave  
STTR, Phase I/II



May 2012



Jan 2012

- Ultimately, installation of 8 crab cavity modules around IR1 & IR5
- Complete validation and test of compact CCs in SPS and LHC with beam
- Planning for SPS tests of a complete cryomodule in 2016:  
(Test in LHC IR4 follows in 2017)

<i>Crab Cavity prototypes, SM18 and SPS tests</i>	2012				2013				2014				2015				2016			
LS1																				
CC vertical tests in SM18																				
Test cryostat design																				
Test cryostat construction																				
SM18 test of proto cryomodule																				
SPS Beam testing																				
SPS Cryo 2k & upgrade (Details to be defined with Cryo)																				
Vacuum work at COLDEX 41737 (2-3 weeks needed)																				
SLAC Collimator installation in SPS (TbD)																				
RF Power installation in SPS																				

SPS working for a complete integration study (A. Macpherson)  
All infrastructure, cryo, RF and services will be performed

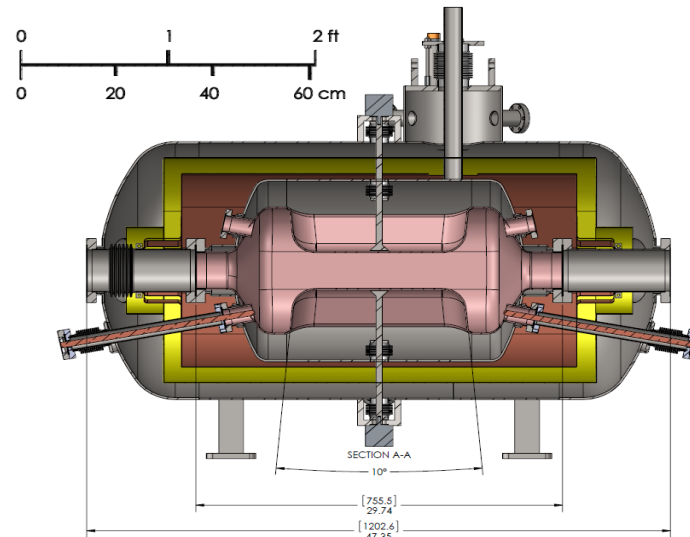
Collaboration with US & European partners

FNAL launching a proposal to DOE (Tom Peterson et al.)

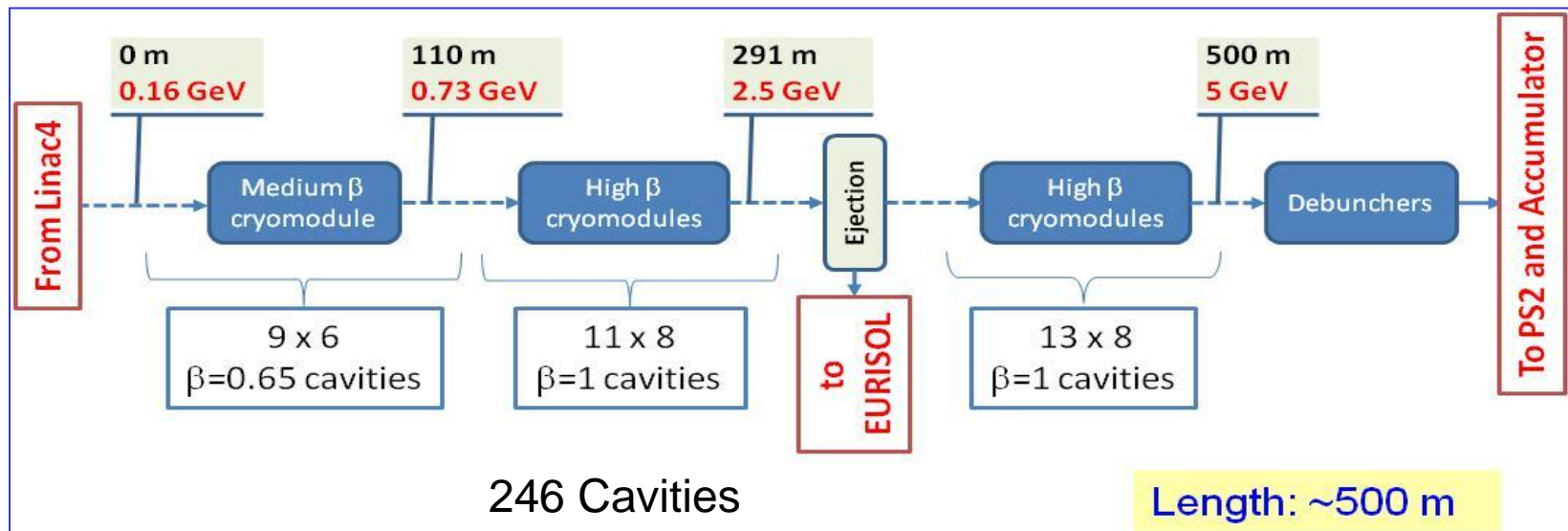
Triumph keen on collaborating on CM

ODU-Niowave: Phase I SBIR for cryomodule approved

ODU-Niowave  
SBIR, Phase I



- **LP-SPL:** SC-linac (160 MeV to 4 GeV) with ejection at intermediate energy
- High gradient: 25 MV/m at 704 MHz in  $\beta = 1$  section.
- Part of the upgrade of the CERN injectors, with PS2
- **HP-SPL:** High Intensity Higher Energy SC-linac (160 MeV<sup>®</sup> 5 GeV) with ejection at intermediate energy
  - Longer duty cycle
  - New klystron modulators, upgraded infrastructure (cooling & electricity, etc.)
  - 5 additional  $\beta = 1$  cryomodules to reach 5 GeV ( $\pi$  production for  $\nu$  Factory)





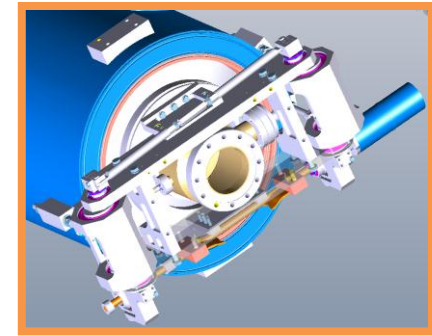
In 2010, original upgrade plan for LHC injectors abandoned

However, program launched for **study of SC RF for high intensity proton driver** in the context of possible future neutrino facilities at CERN, based on the LP/HP-SPL.

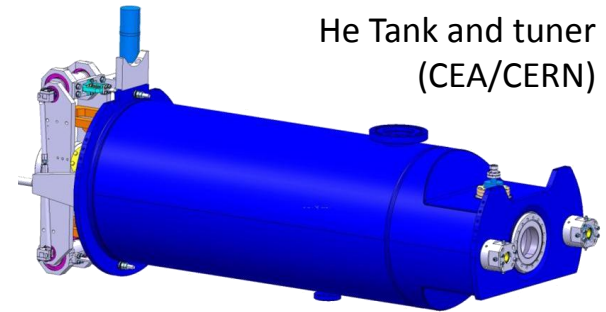
- Included in CERN MTP, with resources.
  - Comprises:
    - Continuation of design work on HP-SPL, excluding integration & site specifics.
    - Includes prototyping of critical components: **high gradient cavities, RF ancillaries and the construction of a test cryomodule**
    - Upgrade of clean room and assembly facilities at CERN
    - Preparation of a power test stand
  - Plan to power test the cryomodule in 2014 (CERN SM18)
  - Updated CERN yellow report on SPL to be completed by mid 2012
- 
- [SPL documentation](https://edms.cern.ch/nav/SLHC-000008) in EDMS [ <https://edms.cern.ch/nav/SLHC-000008> ]
  - [SPL meetings](http://indico.cern.ch/categoryDisplay.py?categId=1893) in Indico [ <http://indico.cern.ch/categoryDisplay.py?categId=1893> ]



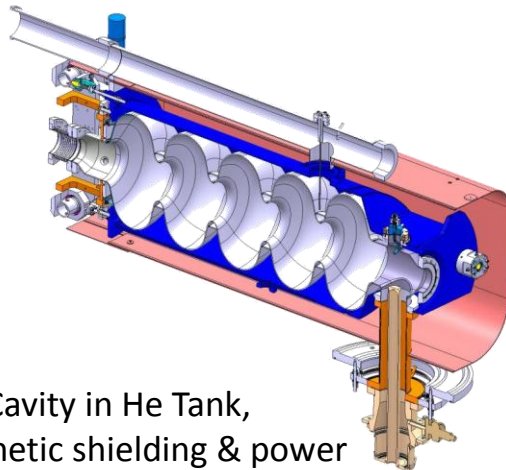
- **Collaboration with CEA Saclay** - Cavity design by Saclay
  - Low  $\beta$  protos built & tested at CEA
  - Tuner design & construction by Saclay
  - He tank & cryomodule designs ongoing (CEA/CERN)
  - Four  $\beta = 1$  5-cell cavities being made in industry
  - Test on single cell cavity ongoing at CERN,
  - Tests on first 5-cell cavity expected soon
- **Close collaboration with European Spallation Source (ESS) in Lund**
  - **Strong synergy with LHeC !**  
 R&D directly applicable to LHeC ERL  
 And close synergy with BNL work for eRHIC at 704 MHz



CEA Tuner



He Tank and tuner  
(CEA/CERN)



SPL Cavity in He Tank,  
magnetic shielding & power  
coupler



BNL 704 MHz cavity  
(20 MV/m with high  
 $Q_0$  demonstrated)



# SC RF Prototype Design and Cryogenics

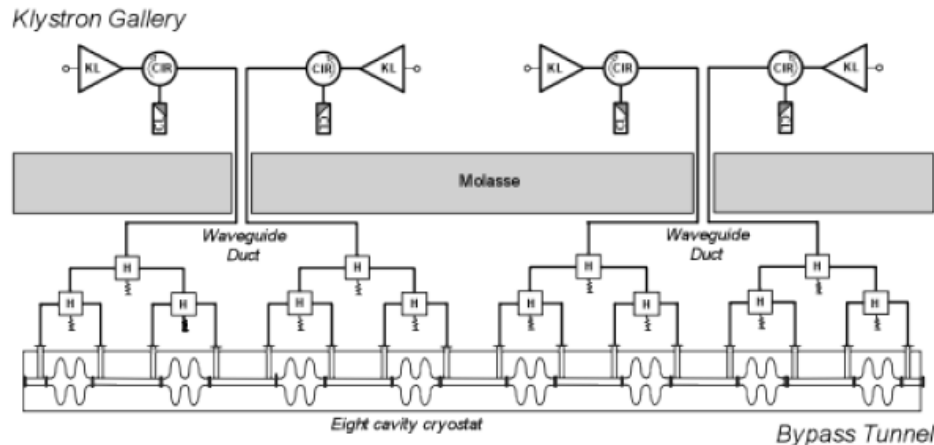
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## RF from design report:

- 560 MV, 721.42 MHz cw RF
- 112 two cell cavities at 11.9 MV/min
- 14 cryomodules of ~ 10 m, 8 at CMS and 3+3 at ATLAS
- One 1 MW klystron feeding 2 cavities, 56 total
- One 6 MVA Power Converter per 4 klystrons on surface
- Total 49 MW klystron RF power, 79 MW grid power



RF distribution layout for an 8-cavity cryomodule

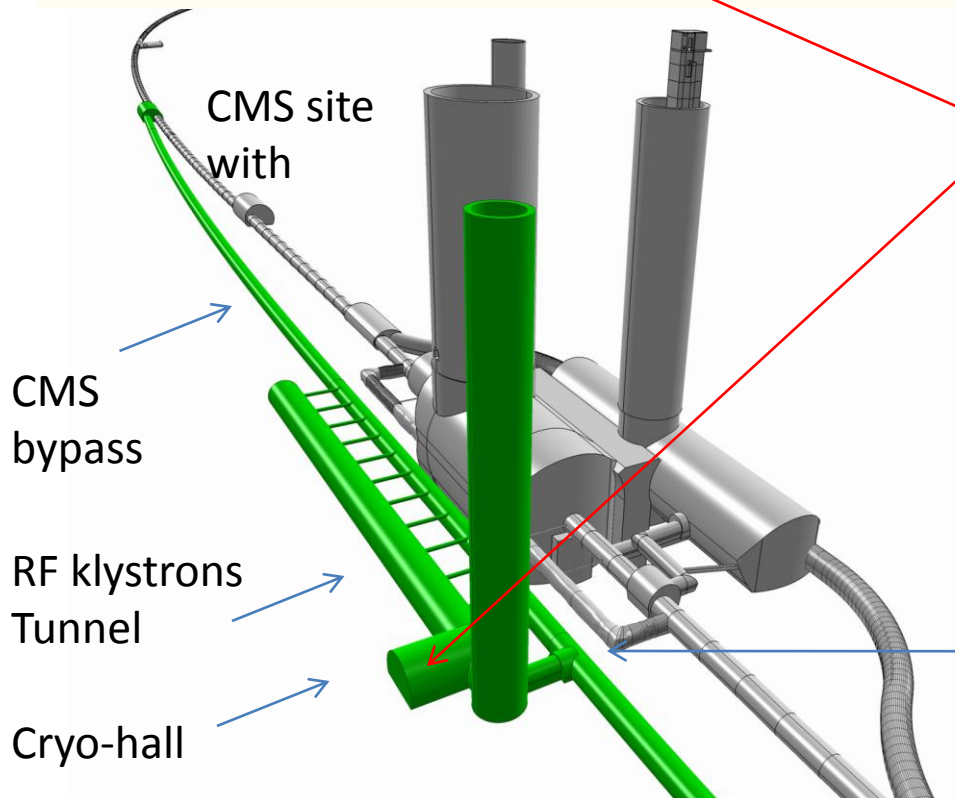
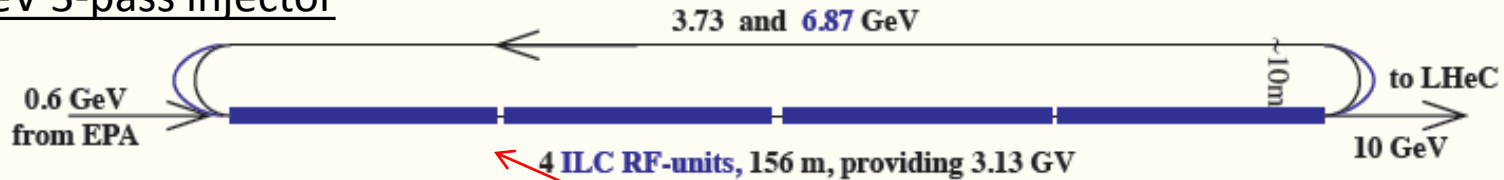
Energy	GeV	60
Beam current	mA	100
Synchrotron losses	MeV/turn	437
Power loss to synchrotron radiation	MW	43.70
Bunch frequency (25 ns spacing)	MHz	40.08
Multiplying factor		18
RF frequency	MHz	721.42
Harmonic number		64152
RF Voltage for 50 hour quantum lifetime	MV	500.00
Nominal RF voltage (MV)	MV	560.00
Synchronous phase angle	degrees	129
Quantum lifetime at nominal RF voltage	hrs	infinite
Number of cavities		112
Number of 8-cavity cryomodules		14
Power couplers per cavity		2
Average RF power to beam per power coupler	kW	195
Voltage per cavity at nominal voltage	MV	5.00
Cells per cavity		2
Cavity active length	m	0.42
Cavity R/Q		114
Cavity Gradient	MV/m	11.90
Cavity loaded Q (Matched)		$2.8 \cdot 10^5$
Cavity forward power (nom. current, nom. voltage) for matched condition	kW	390
Nominal cavity loaded Q (matched for 50 % more beam)		$1.9 \cdot 10^5$
Cavity forward power (nominal current, voltage & loaded Q)	kW	406
Forward power per coupler	kW	203
Number of cavities per klystron		2
Waveguide losses	%	7
Klystron output power	kW	870
Feedbacks & detuning power margins	%	15
Klystron rated power	kW	1000
Total number of klystrons		56
Total average operating klystron RF power	MW	49
DC power to klystrons assuming 65% klystron efficiency	%	75
Grid power for RF, assuming 95% efficiency of power converters	MW	79



# Ring-Ring Cryogenics – Injector & CMS



## 10 GeV 3-pass injector

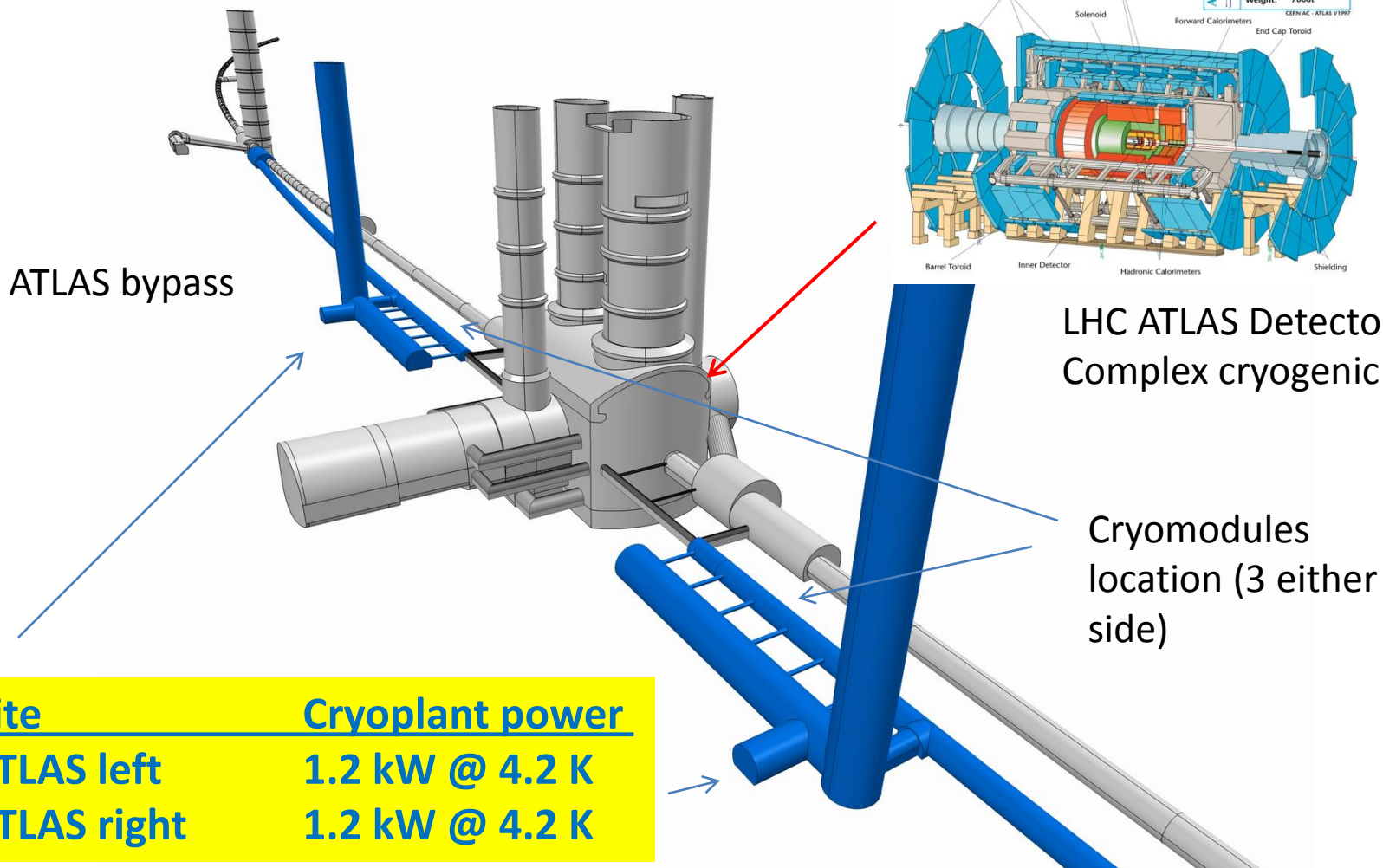


Site	Cryoplant power
Injector	2.0 kW @ 4.2 K
CMS	3.0 kW @ 4.2 K
ATLAS left	1.2 kW @ 4.2 K
ATLAS right	1.2 kW @ 4.2 K
2 K operation of cryomodules	

Acc. String with  
8 cryomodules  
At CMS



# Ring-Ring Cryogenics - ATLAS





## From design report: Linacs

- 60 GeV
- Two 10 GeV Linacs, 0.3 GeV injection and 6 linac passes
- 6.6 mA beams
- 5-cell cavity at 20 MV/m (20.8 MV per cavity) 721.42 MHz
- $Q_o = 2.5 \text{ E}10$
- 480 cavities per linac (960 in total)
- 60 cryomodules of  $\sim 15.5$  m length per linac (990 m)
- One 21 kW rated (solid state) power source per cavity
- RF and controls in separate tunnel
- 24 MW grid power for RF

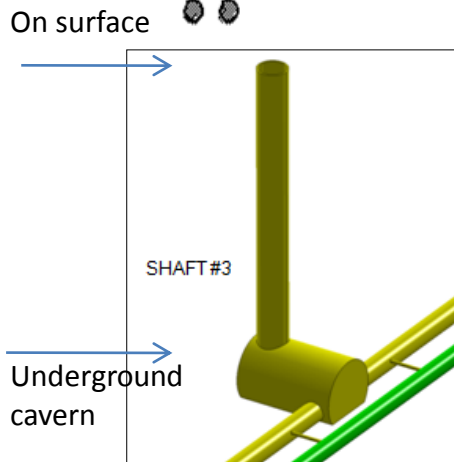
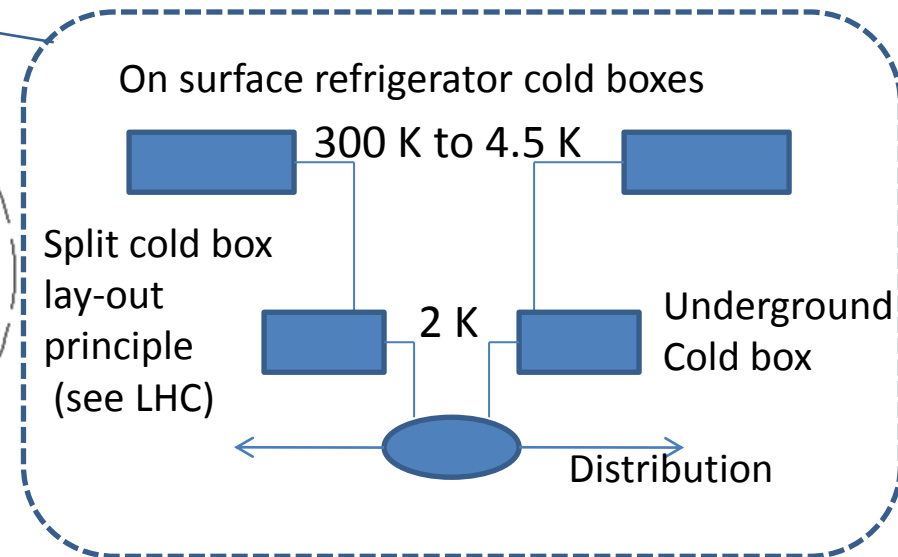
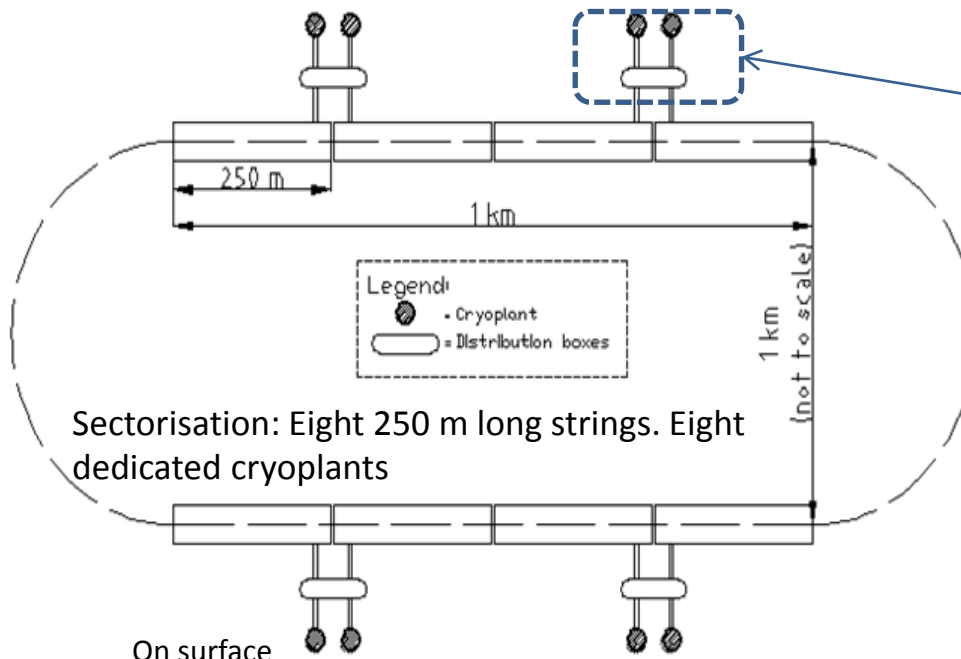
## Arc RF systems – if needed ..

- 1442/721 MHz - 58/38 cavities
- 10.5 MW RF, 23 MW Grid power

Parameter	Unit	Value
Total energy loss in 20-60GeV arcs	MeV	1885.3
Power loss in 20-60GeV arcs	MW	12.4
Arc RF frequency	MHz	1442/721
Number of cavities		58/38
Number of klystrons		31/10
Total average supplied klystron RF power	MW	10.5
Assumed overall conversion efficiency - grid to klystrons RF out	%	60
Grid power for arc RF systems	MW	23

Parameter	Unit	Main RF system
Beam energy	GeV	60.0
Injection energy	GeV	0.3
Average beam current out	mA	6.6
Av. accelerated beam current in linacs	mA	19.8
Required total voltage in both linacs	GV	20.0
Energy recovery efficiency	%	96
Total power needed to compensate recovery losses	MW	15.8
RF frequency	MHz	721.42
Gradient	MV/m	20
Cells per cavity		5
Active cavity length	m	1.04
Cavity voltage	MV	20.8
Number of cavities		960
Energy gain per cycle	GeV	20
Power to compensate recovery losses per cavity	kW	16.5
Cavity R/Q	circuit $\Omega$	285
Cavity unloaded Q [ $Q_o$ ]	$10^{10}$	2.5
Loaded Q [ $Q_{ext}$ ]	$10^6$	46
Cavity forward power	kW	16.5
Cavity forward power - no beam	kW	4.1
Number of cavities per solid state amp.		1
Transmission losses	%	7
Amplifier output power per cavity	kW	17.6
Feedbacks power margin	%	15
Amplifier rated power	kW	21
Total number of amplifiers		960
Total average amplifier output power	MW	16.9
Assumed overall conversion efficiency grid to amplifier RF output	%	70
Grid power for linacs RF (without cryogenics power)	MW	24





Split cold boxes (see LEP2, LHC (4.2K on surface, 2K in tunnel))

Total (minimum) cooling power;  
**84 kW @ 4.2 K** (no contingency)  
**Cryoplants proposed**  
**8 x 10.5 kW @ 4.2 K (21 MW Grid)**  
 R&D cavities ongoing.  
 Expectance for improved Q values.....

# Detector Cryogenics

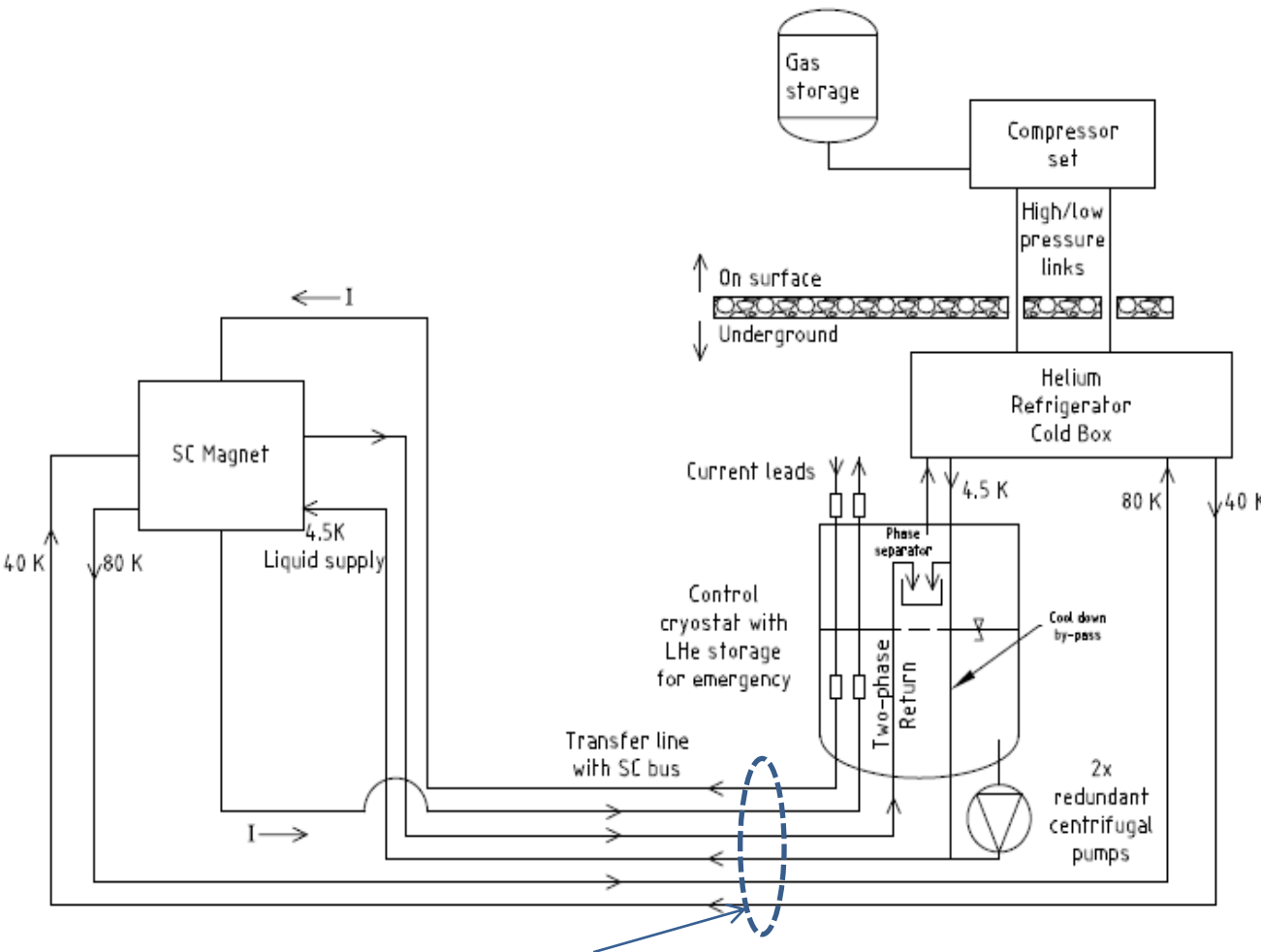
## SC Solenoid and dipoles

### Principle flow-scheme

He Cryostat and phase separator

Redundant centrifugal pumps

Similar to Atlas Test Facility H180

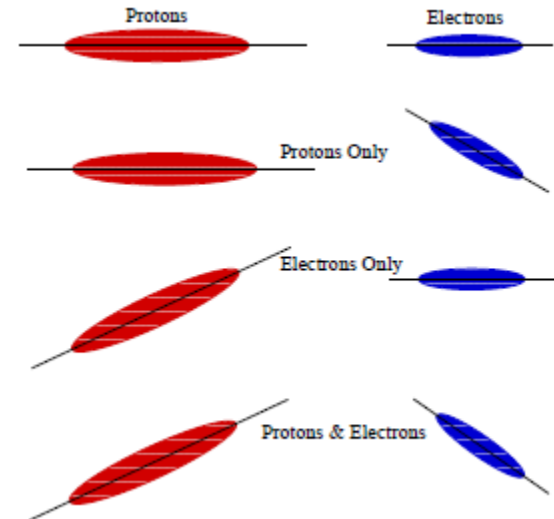


SC bus integrated in transfer line

## Stand by option from design report: (R. Calaga)

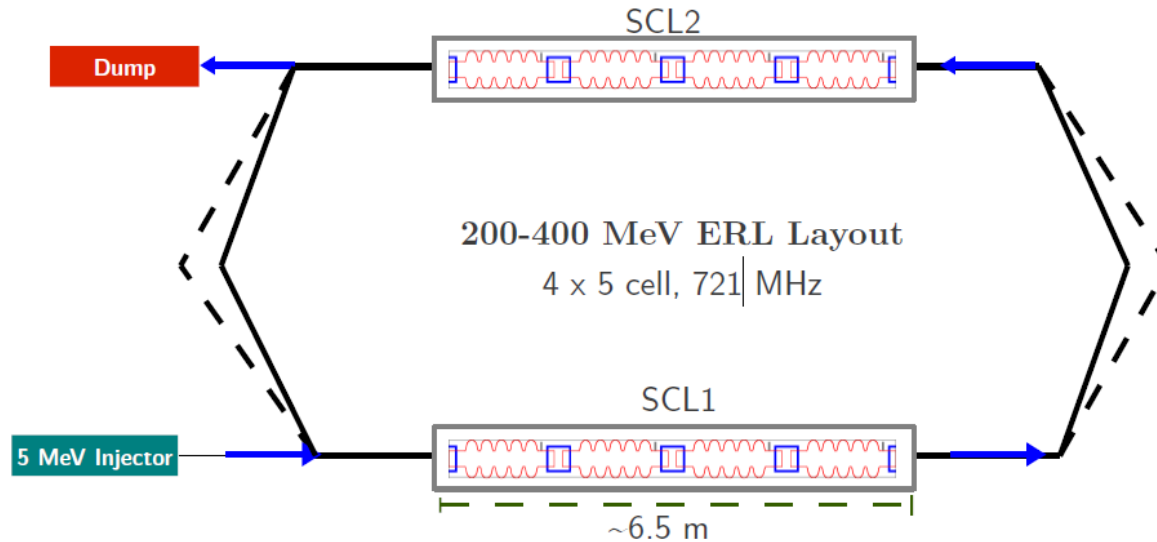
- Crossing angle is 1 mrad for beam separation, incurs a moderate loss
- Depending on design of quadrupoles for proton beam, effect may be greater
- Crabbing options for both proton & electron beams
- The more significant luminosity gain is by uncrossing the proton beam
- CC Technology for HL-LHC is directly applicable
  - See previous slides on CC cryomodule testing

Scenario	L/L <sub>0</sub>	
	400 MHz	800 MHz
X-Angle (1 mrad)	1.0	
Uncross both $e^-$ and $p^+$	1.88'	1.48
Uncross only $e^-$	1.007	
Uncross only $p^+$	1.88	1.48



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Two 4-cavity cryomodules in LHeC ERL configuration: (R. Calaga)



	units	1-CM	2-CM
Energy	[MeV]	100	200-400
Frequency	[MHz]	721	721
Charge	[pC]	~500	~500
Rep rate		CW	CW

- Motivation
  - Study behaviour of a high energy multi-pass multiple cavity ERL for LHeC
  - Namely - Optics, RF power requirements, synchronization & delay issues ...
  - HOMs & HOM couplers, Cryogenics, instrumentation, controls, LLRF ...
  - Injector studies DC gun (JLAB) or SRF gun FZR Rossendorf, BNL
  - Reliability issues, operation issues
  - Could be foreseen as the injector to LHeC ERL ? (See E. Jensen's talk)
- Specs
  - High Energy  $\sim 0.5$  GeV, and CW.
  - High beam current: 40 -100 mA ?
  - At least 2 passes (optics studies, synchronization & delay issues)
  - Multi cavity cryomodule
  - Two Linac layout as Lhec ERL
- Other Physics Motivation:
  - ERL demonstration, FEL,  $\gamma$ -ray source, eCooling ? (@PS/SPS energies),
  - Ultra short electron bunches
- Potentially one of first low-frequency SC-ERL test facilities
  - Synergy with SPL-ESS, JLAB & BNL activities.



- Feasibility
  - SPL type CMs are being produced. Only minor frequency & coupler adjustment needed for LHeC
- Infrastructure
  - Need cryogenics, shielding, electricity, water, RF power, LLRF & Controls
- Location
  - SM18 or close to SM18 a first obvious suggestion, cryo availability, already has RF activity.
  - Cryo Capacity would be sufficient
  - Sharing of cryo ?
  - **All equipment could be eventually be reused, for example on the injector site**
- Timeline – determined by
  - Availability of cryomodules – in 2014 SPL cryomodule will be ready
  - Time to produce cryostat(s) and introduce 721 MHz cavities
  - 3 years a reasonable estimate ?
- Cost
  - TbD, but material for cryomodule construction ~ 2M CHF each (SPL F. Gerigk))



# SC RF Prototype Design and Cryogenics

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- Optimum frequency
  - 721 MHz a good choice - gradients of  $\sim 20$  MV/m can be achieved with good  $Q_0$
  - Cryo power, HOMs, synergy with CERN R&D and other projects
  
- Highest  $Q_0$  at medium gradients
  - BCP and/or electro-polishing - recipes
  - Surface inspection (optical microscopy or by other means)
  - Diagnostics
    - All part of CERN SCRF activities and infrastructure upgrade
  - Encouraging news from JLAB – Heat treatment at 1400 degrees -  $Q_0 > 4E11$  !! J. Ciovati et al.!
  - Would reduce cryo consumption considerably compared to our estimated  $Q_0$  of  $2.5E10$  in the DR !!
  - Further studies on this and other methods ..
  
- Studies of material other than bulk niobium e.g. Thin films ?  $Nb_3Sn$  ?
  - Sputtered Nb will reduce cost
  - Extensive studies at CERN (T. Junginger)
  - HiPIMS is ongoing CERN/Legnaro/Sheffield – First cavity tested at Legnaro last week !
  - $Nb_3Sn$  could be studied at CERN (Quad resonator) in collaboration with other labs

- SCRF continues to play a major role in CERN's Flagship accelerators (LEP => LHC)
- Several exciting new projects started or on the horizon
- LHeC and its prototyping are exciting and challenging projects which embody synergies with projects inside and outside CERN
- The SRF team at CERN is modest but the activities are growing steadily
- Collaboration with other Labs on SRF issues such as cavity and component preparation, surface treatments, new materials, assembly procedures, tests and diagnostics, cryostat and cavity ancillary design are being actively pursued.
- Much of what is needed is in place and the time is right to embark, jointly with collaborating institutes, on construction of an ERL test facility.

## Acknowledgements:



“Common research Infrastructure for Synergies in Physics” For manpower support for Infrastructure upgrades, SPL and ISOLDE work.



For support for Crab Cavity activities

## Thank you for your attention