SC Cavities R&D for LHeC and HE-LHC

Erk Jensen, BE-RF

Many thanks to O. Brunner, E. Ciapala, R. Calaga, S. Calatroni, T. Junginger, D. Schulte, E. Shaposhnikova, J. Tückmantel, W. Venturini, W. Weingarten

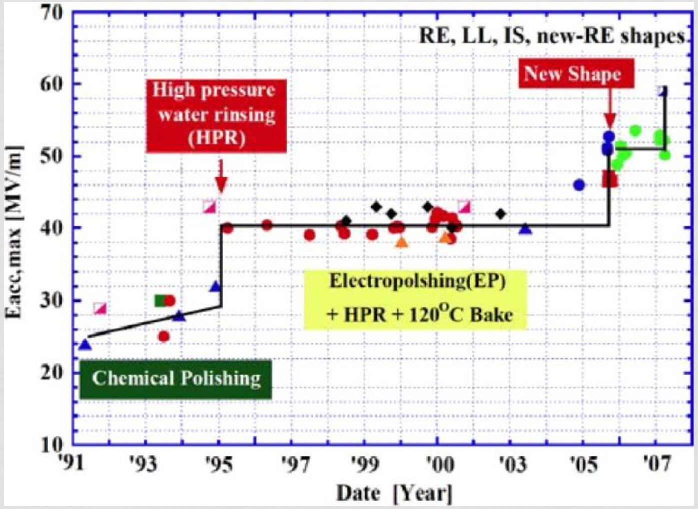
and all those I forgot to mention

SRF Landscape of Challenges

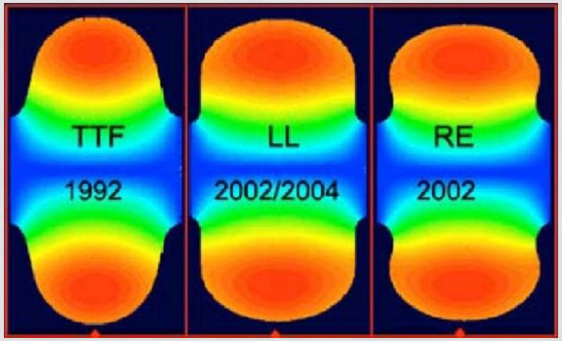
SRF Landscape of Challenges

High Gradient

- **ILC** requires maximum gradient – design 35 MV/m
- **X-FEL** (@DESY) – same technology, reduced gradient ()
- huge R&D effort over the last 20 years – gigantic progress
- Highly sophisticated technology developed:
  - CP(1991), EP, HPWR*(1995), large-grain Nb, optimized shape (2005)
  - new technologies: megasonic rinsing, steam cleaning, horn ultrasonic rinsing



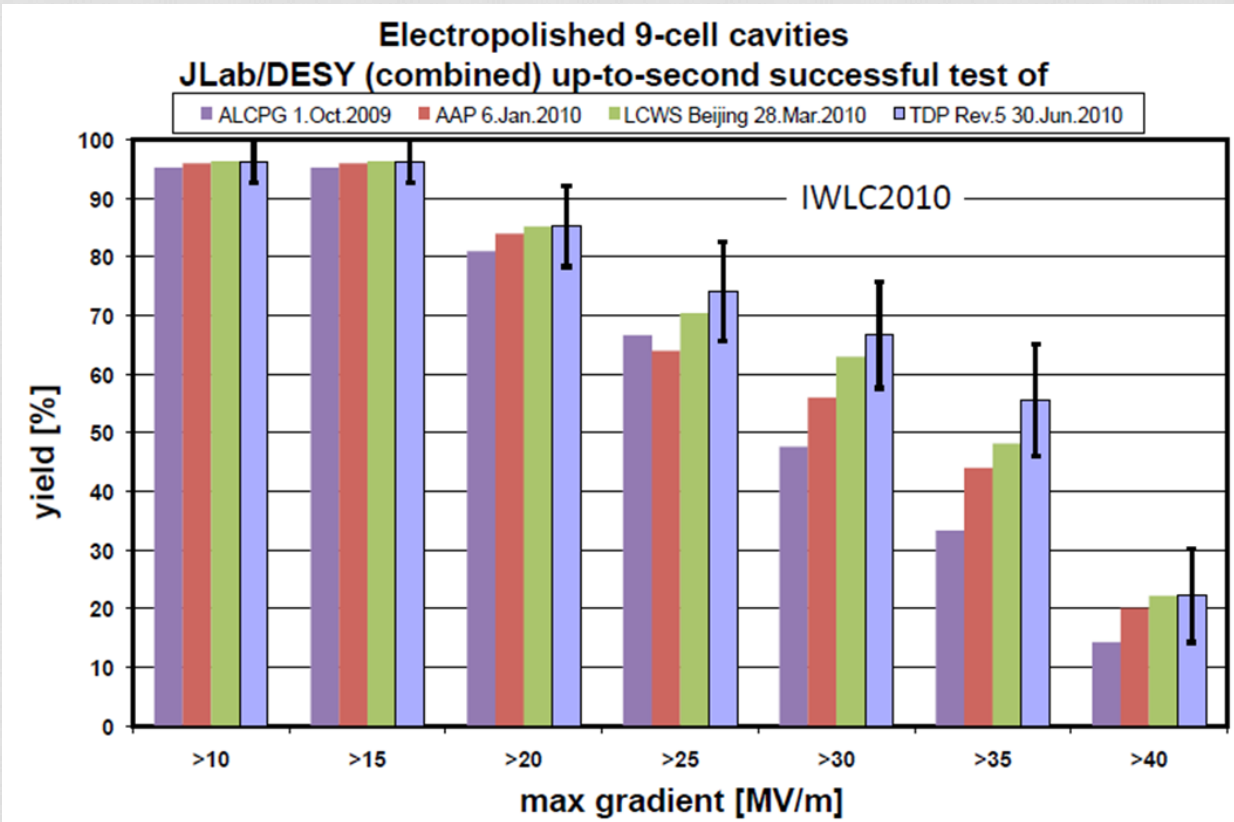
*) initially for LEP2, D. Bloess



A. Yamamoto: IEEE Trans. **AS19**#3, 2009

High gradient & reproducibility, industrialisation

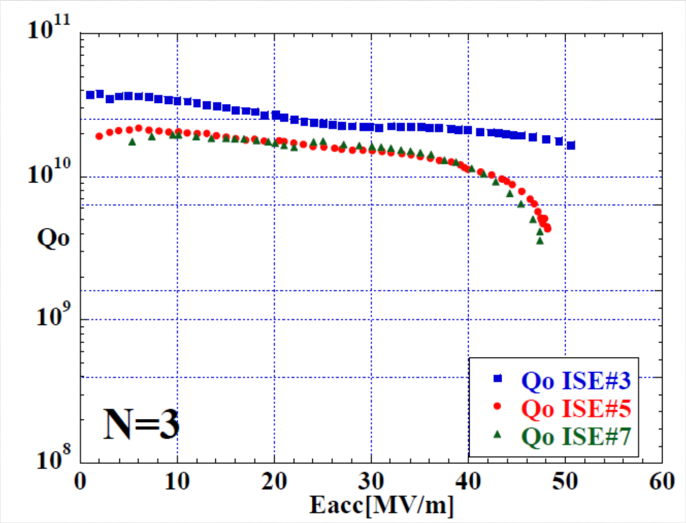
- ILC goal (>90% at 35 MV/m)



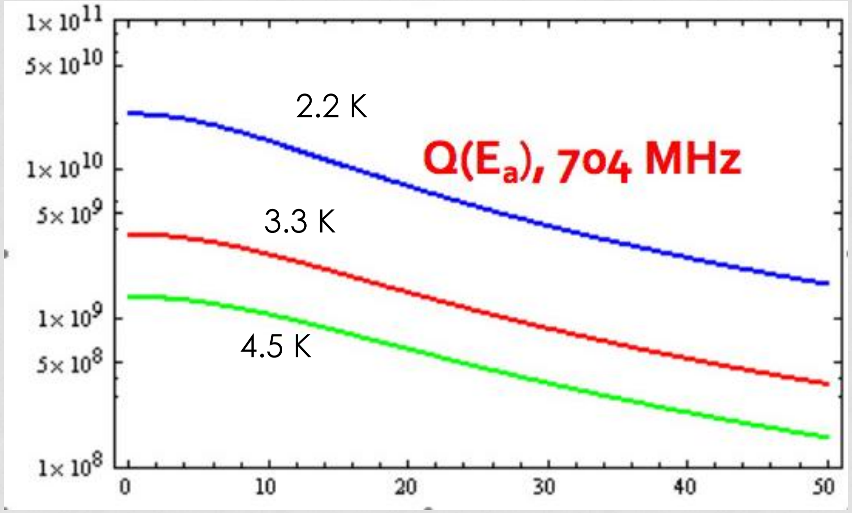
B. Barish: LCWS11, Granada, 2011

RF-Losses, *Q*-slope, *Q*-drop

- It is generally observed that the Q decreases with increasing field.
- Sketch of a possible explanation (W. Weingarten, T. Junginger):
  - Material imperfections lead to nucleation centres, where unpaired (normal-conducting) electrons exist;
  - with increasing field, more and more of these normal-conducting electrons contribute to the current and losses increase

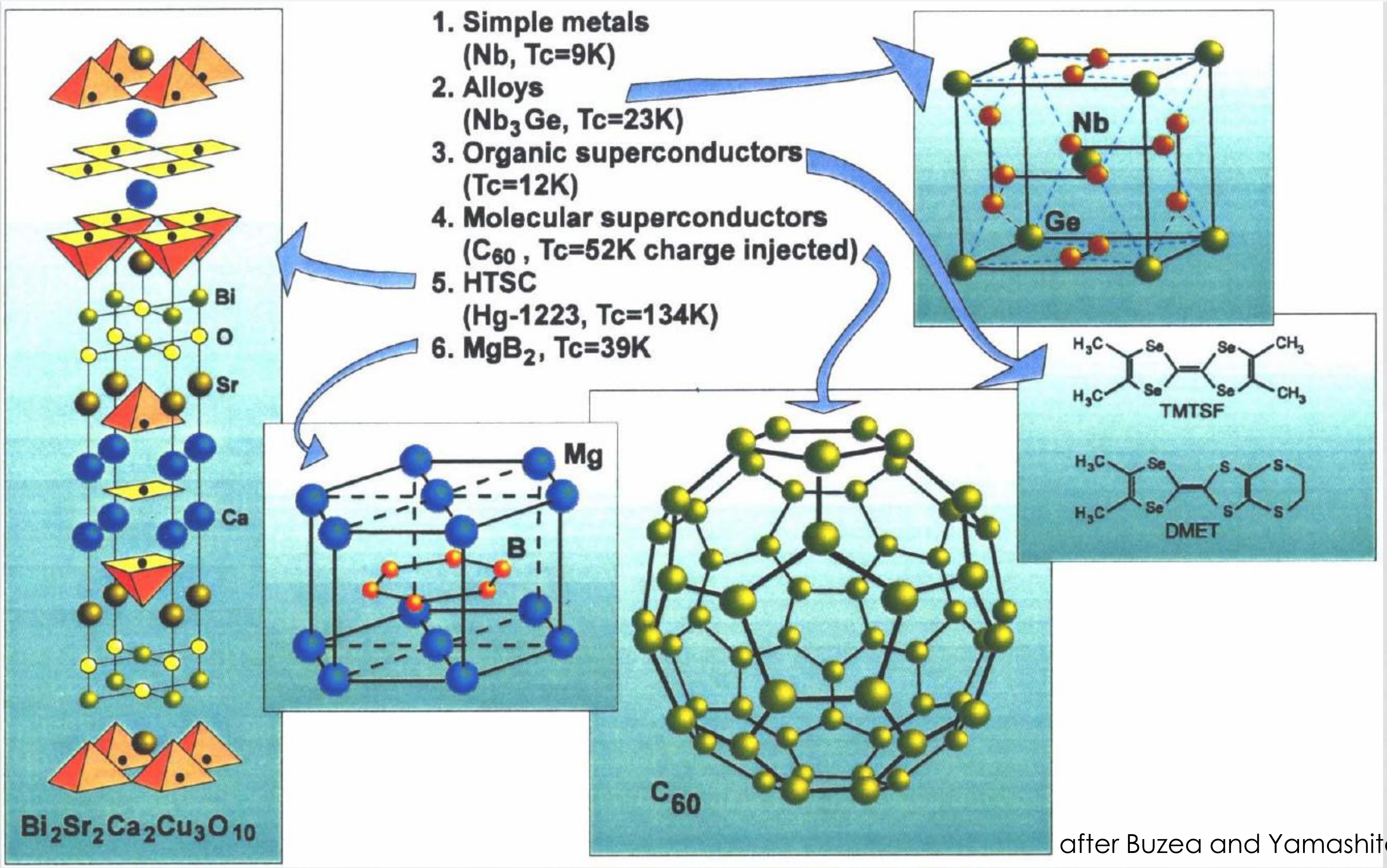


F. Furuta et al., IPAC'10, Kyoto
1.3 GHz, single cell, "Ichiro cavity"



Approximated Q-slopes for a 704 MHz cavity, from F. Gerigk et al., CERN-AB-2008-064

New SC Materials



after Buzea and Yamashita

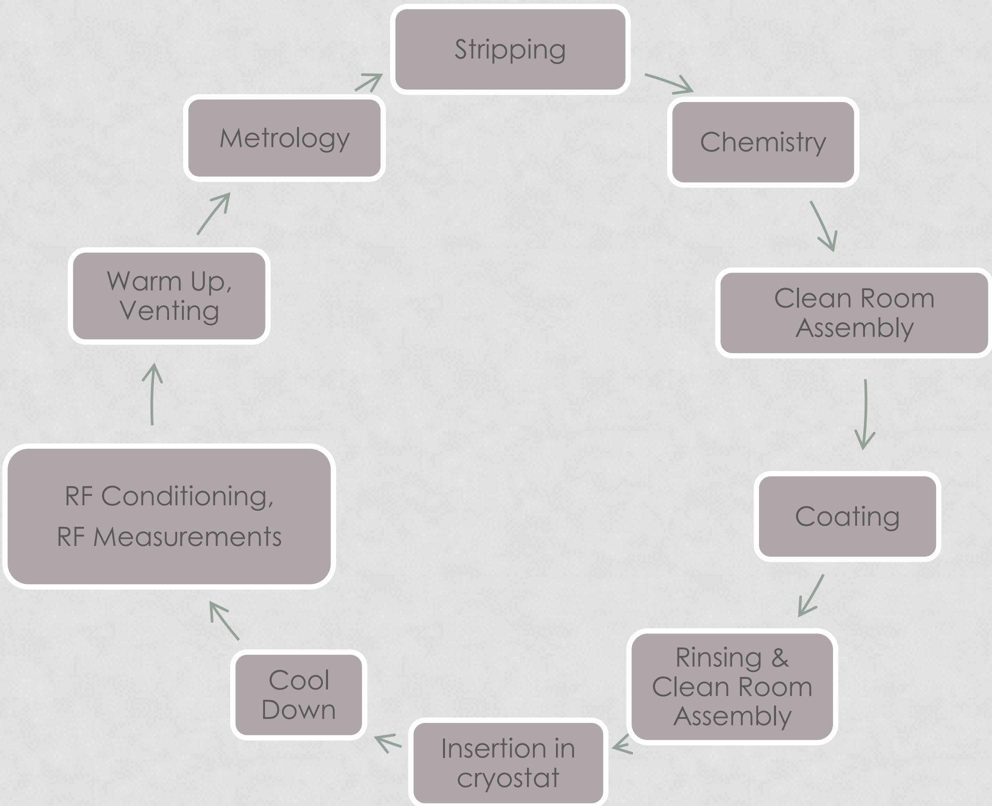
V. Palmieri: Applied Superconductivity, CERN Academic Training Lecture Regular Programme, 2007

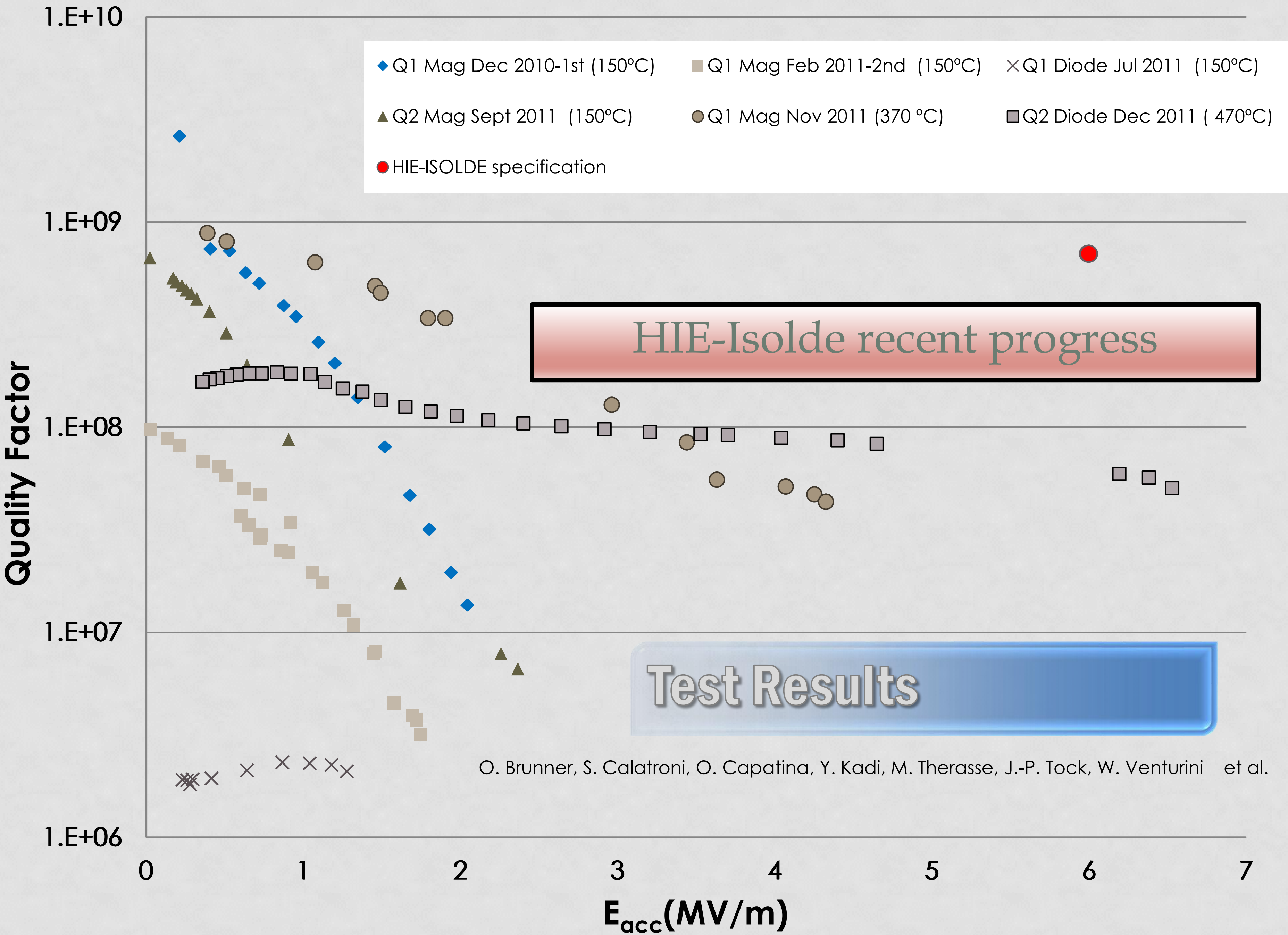
Sputtering Nb on Cu

S. Calatroni: Niobium Coating Techniques, Journal of Physics: Conference Series **114** (2008)

- Advantages:
  - Due to the high cost of Nb, this can reduce cost!
  - The Cu substrate increases the mechanical & thermal stability (quench resistance).
- Technology initially developed at CERN (Benvenuti, LEP, 1980); experts today at JLAB, Legnaro, Saclay, Sheffield & CERN
- Technique used today for ALPI (LNL), Soleil, LHC & HIE-Isolde
- Today, the max. fields are still smaller than for bulk Nb – is this an intrinsic limitation? An interesting field of R&D!
  - Can this technique be extended to new materials? (NbTiN, V_3Si, Nb_3Sn, HTS?)
  - ***Very interesting, promising R&D – large potential!***

SRF specific technology & infrastructures

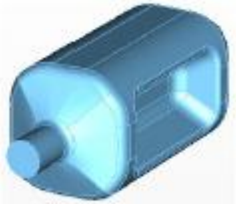


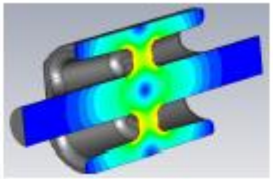

1.E+10
1.E+09
1.E+08
1.E+07
1.E+06
Quality Factor
0
1
2
3
4
5
6
7
Eacc(MV/m)
Q1 Mag Dec 2010-1st (150°C)
Q1 Mag Feb 2011-2nd (150°C)
Q1 Diode Jul 2011 (150°C)
Q2 Mag Sept 2011 (150°C)
Q1 Mag Nov 2011 (370 °C)
Q2 Diode Dec 2011 (470°C)
HIE-ISOLDE specification
HIE-Isolde recent progress
Test Results
O. Brunner, S. Calatroni, O. Capatina, Y. Kadi, M. Therasse, J.-P. Tock, W. Venturini et al.

Crab Cavities for HL-LHC (EuCARD, US-LARP, …)

High Luminosity LHC

Very non-standard shapes!



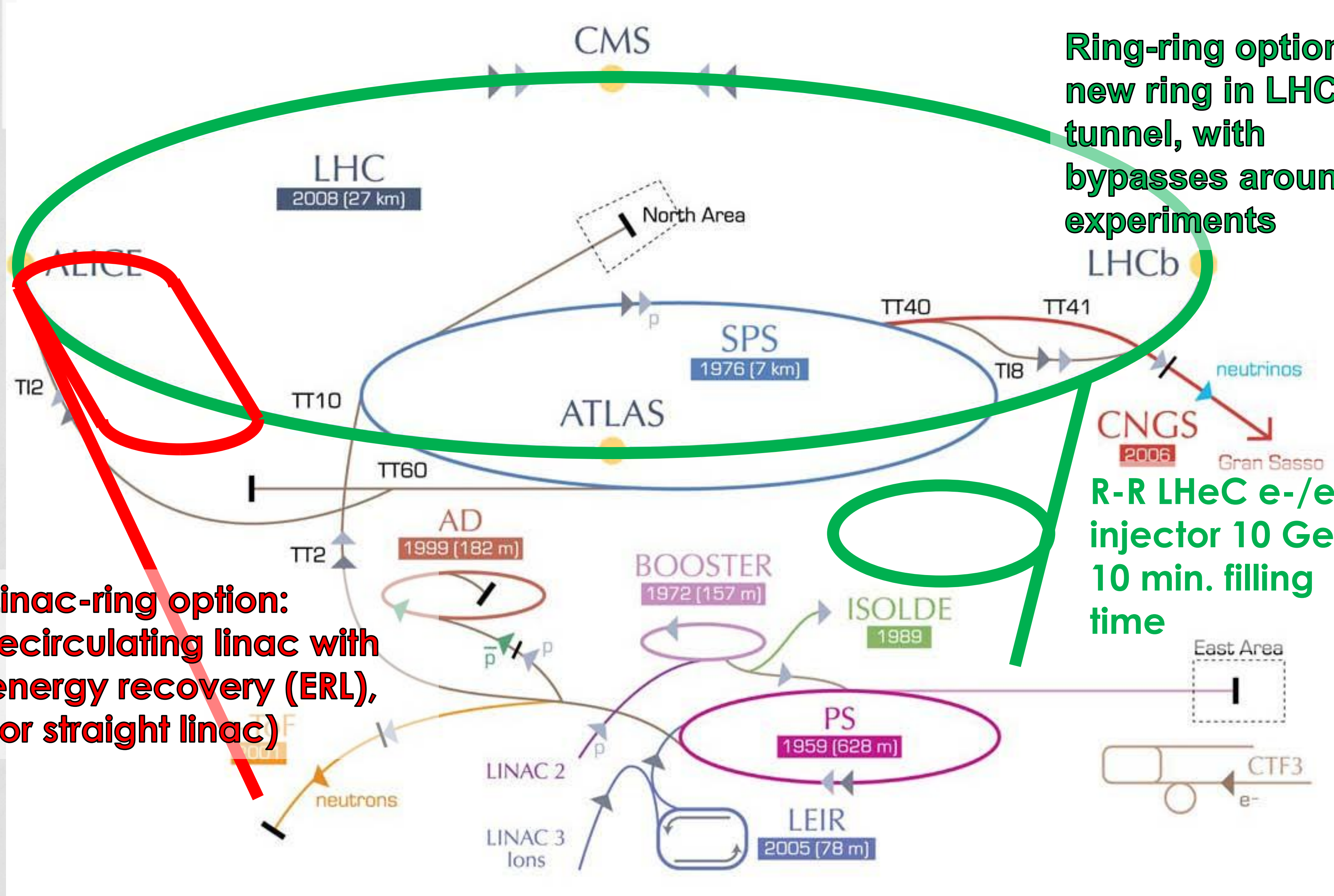


Values for 400 MHz, 3 MV integrated kick	Double ridge (ODU/SLAC)	LHC-4R (ULANC)	¼ Wave (BNL)
Cavity radius [mm]	147.5	143/118	142/122
Cavity length [mm]	597	500	380
Beam Pipe radius [mm]	42	42	42
Peak E-field [MV/m]	33	32	47
Peak B-Field [mT]	56	60.5	71
RT/Q [Ω]	287	915	318
Nearest OOM [MHz]	584	371-378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

LHeC

MOST EXCITING!

LHeC Options: Ring-ring and Linac-ring



Ring-ring option: new ring in LHC tunnel, with bypasses around experiments

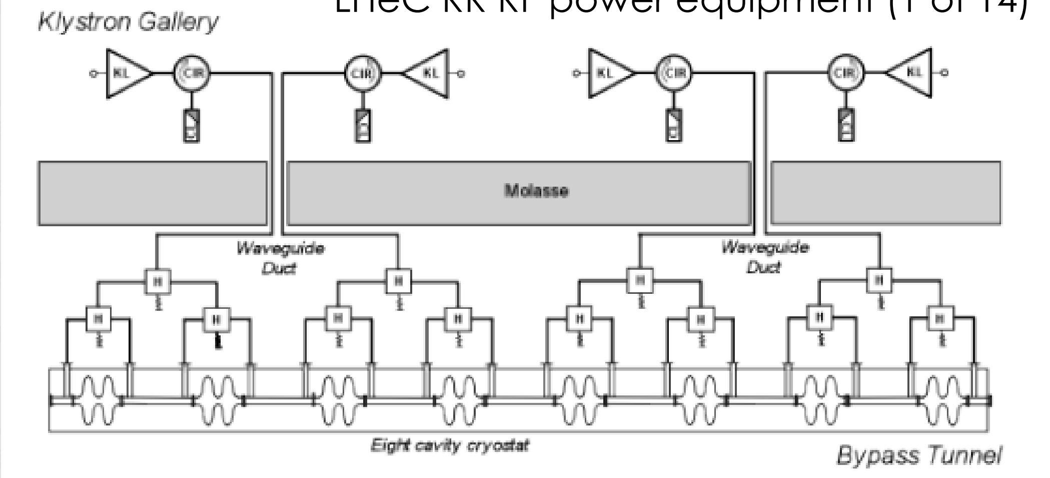
R-R LHeC e-/e+ injector 10 GeV, 10 min. filling time

Linac-ring option: recirculating linac with energy recovery (ERL), (or straight linac)

LHeC Options

- Electron beam: 60 GeV, 100 mA
- **Ring-Ring option**
  - SR power loss: 44 MW
  - *f* = 721.42 MHz, *h* = 64152,
  - total RF voltage: 560 MV
  - 56 x 1 MW klystrons
  - 14 x 8-cavity cryostats
  - Gradient 11.9 MV/m
  - Power consumption: 79 MW
  - RF in bypasses near ATLAS & CMS

LHeC RR RF power equipment (1 of 14)



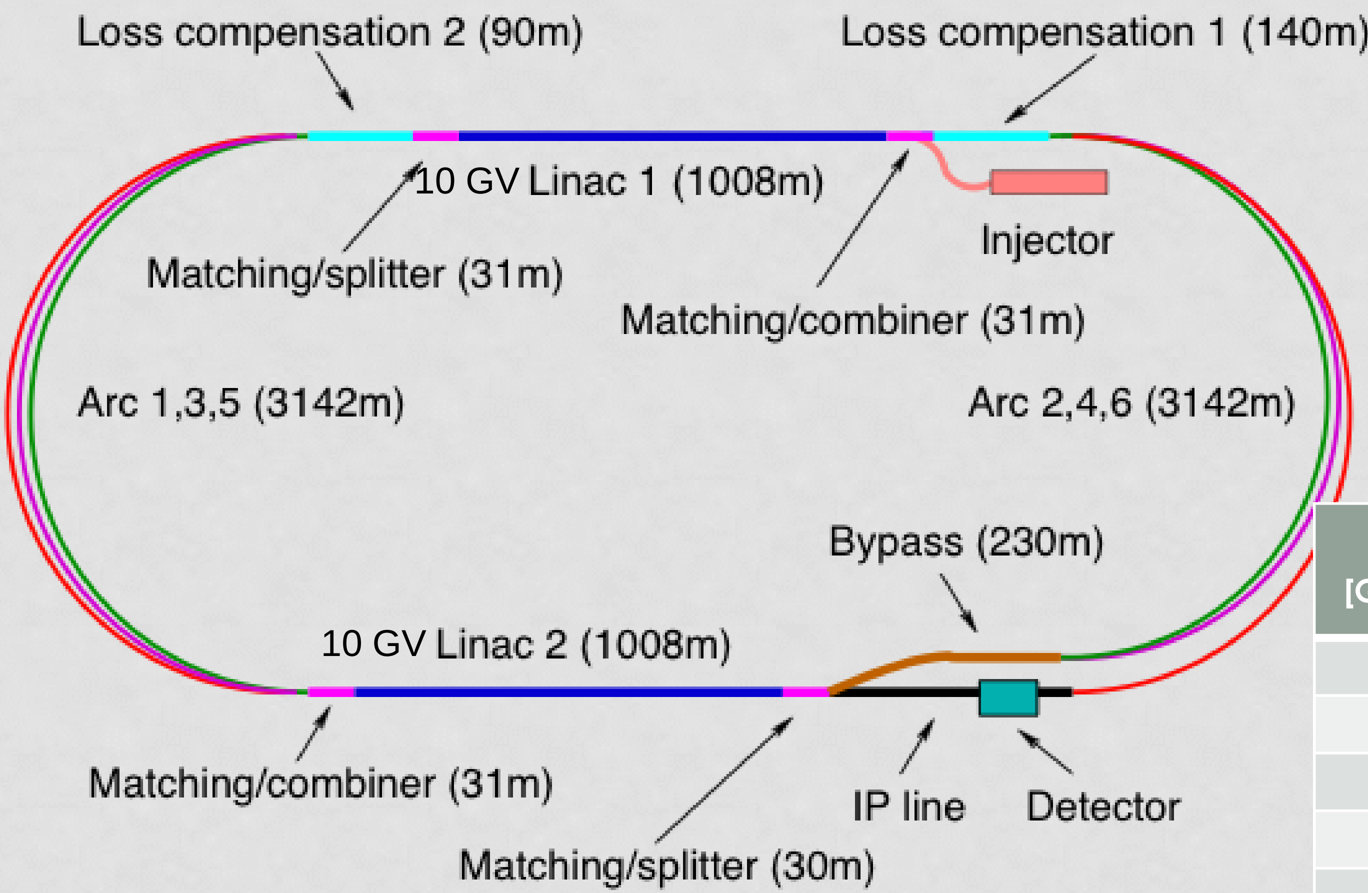
- **Linac-Ring option (I will concentrate on this)**
  - 2 x 10 GeV linacs
  - *f* (*n* x 20.04 MHz): 721.42 MHz (SPL type) or 1322.6 MHz (ILC type)
  - total RF voltage: 2 x 10 GV
  - 721 MHz: 960 x 21 kW amplifiers (e.g. IOT), 1323 MHz: approx. 120 x 180 kW klystrons (e.g.)
  - Gradient 20 MV/m
  - Power consumption (rough estimate): 79 MW (721 MHz) or 91 MW (1323 MHz)

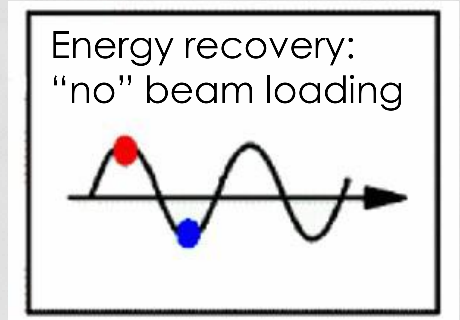
preliminary – needs x-check!

LHeC parameters

	Units	Protons	RR e-	LR e-
energy	[GeV]	7000	60	60
frequency	[MHz]	400.79	721.42	721.42
norm. ε	[mm]	3.75	50	50
I_{beam}	[mA]	>500	100	6.6
Spacing	[ns]	25, 50	50	50
bunch population		$1.7 \cdot 10^{11}$	$3.1 \cdot 10^{10}$	$2.1 \cdot 10^{9}$
bunch length	[mm]	75.5	0.3	0.3

Energy Recovery Linac – ERL



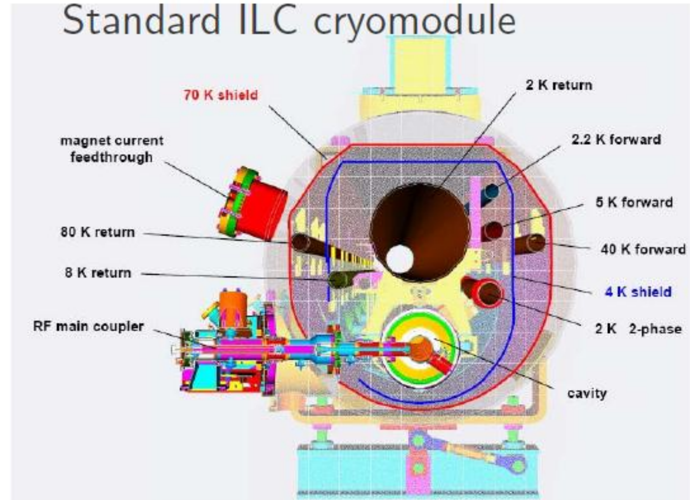


E [GeV]	Energy lost (SR) [MeV]	RF power [MW]
10	2 x 0.6	0.01
20	2 x 9.3	0.12
30	2 x 47	0.62
40	2 x 48	1.96
50	2 x 362	4.78
60	750	4.95

Potential Options

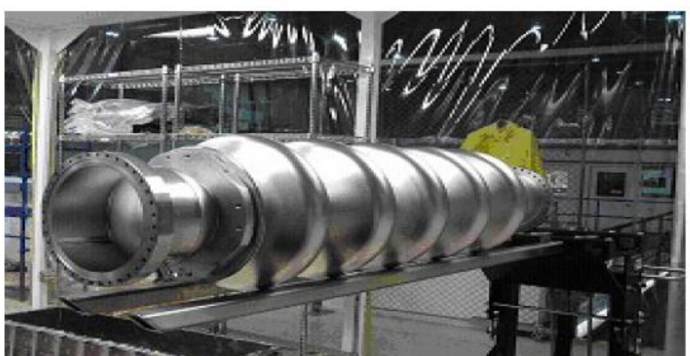
1.3 GHz

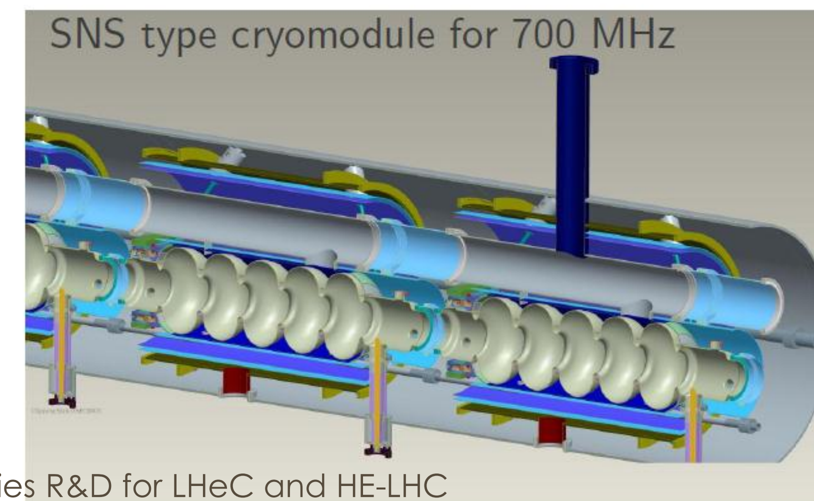
ILC Collaboration



704 MHz

ESS, eRHIC, SPL

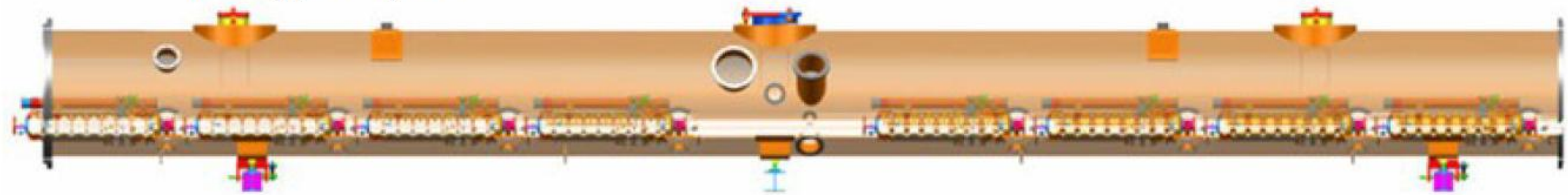




Cryo-module layout

1.3 GHz ILC Type Layout

9-cell cavities (1.53 m long), 8 per cryo-module



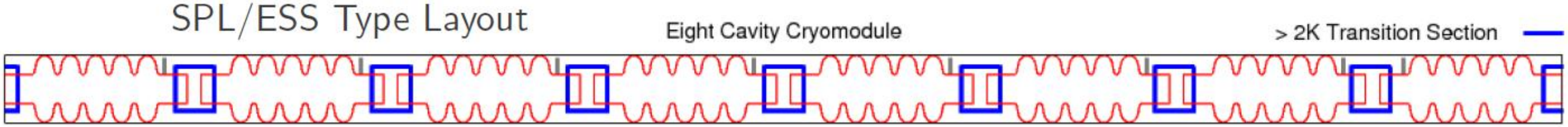
~12 m, 167 MeV/Module

120 CM's

704 MHz

SPL/ESS Type Layout

5-cell cavities (1.6 m long), 8 per cryo-module



~13 m, 167 MeV/Module

120 CM's

Approx cavity length is similar if not same

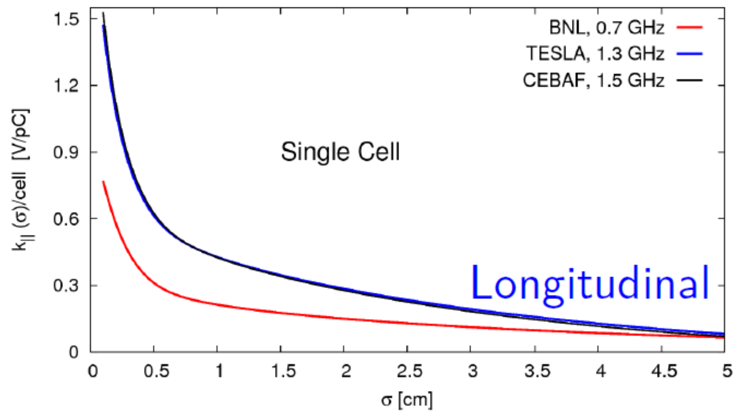
ILC type cryomodule can be utilized for both frequencies

Loss factors

Longitudinal modes:

$$P_{ave} = (k_{loss} Q)\, I_{beam}$$

$$k_{(loss)} \propto \frac{1}{R_{(iris)}} \sqrt{\left(\frac{d}{\sigma_z}\right)} \sqrt{(N_c)}$$



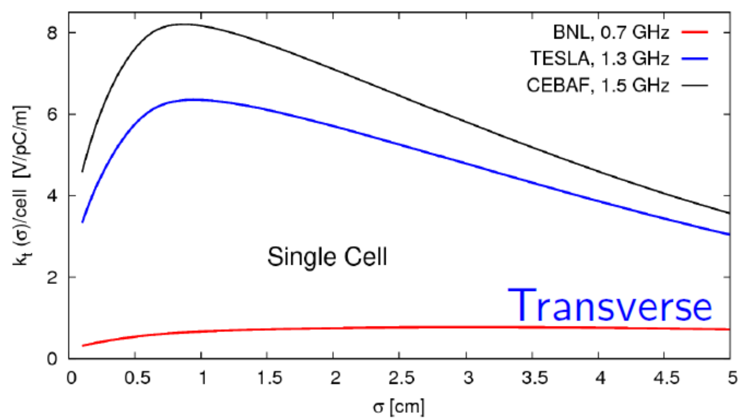
Limit, max power → 2K

R. Calaga

Transverse modes:

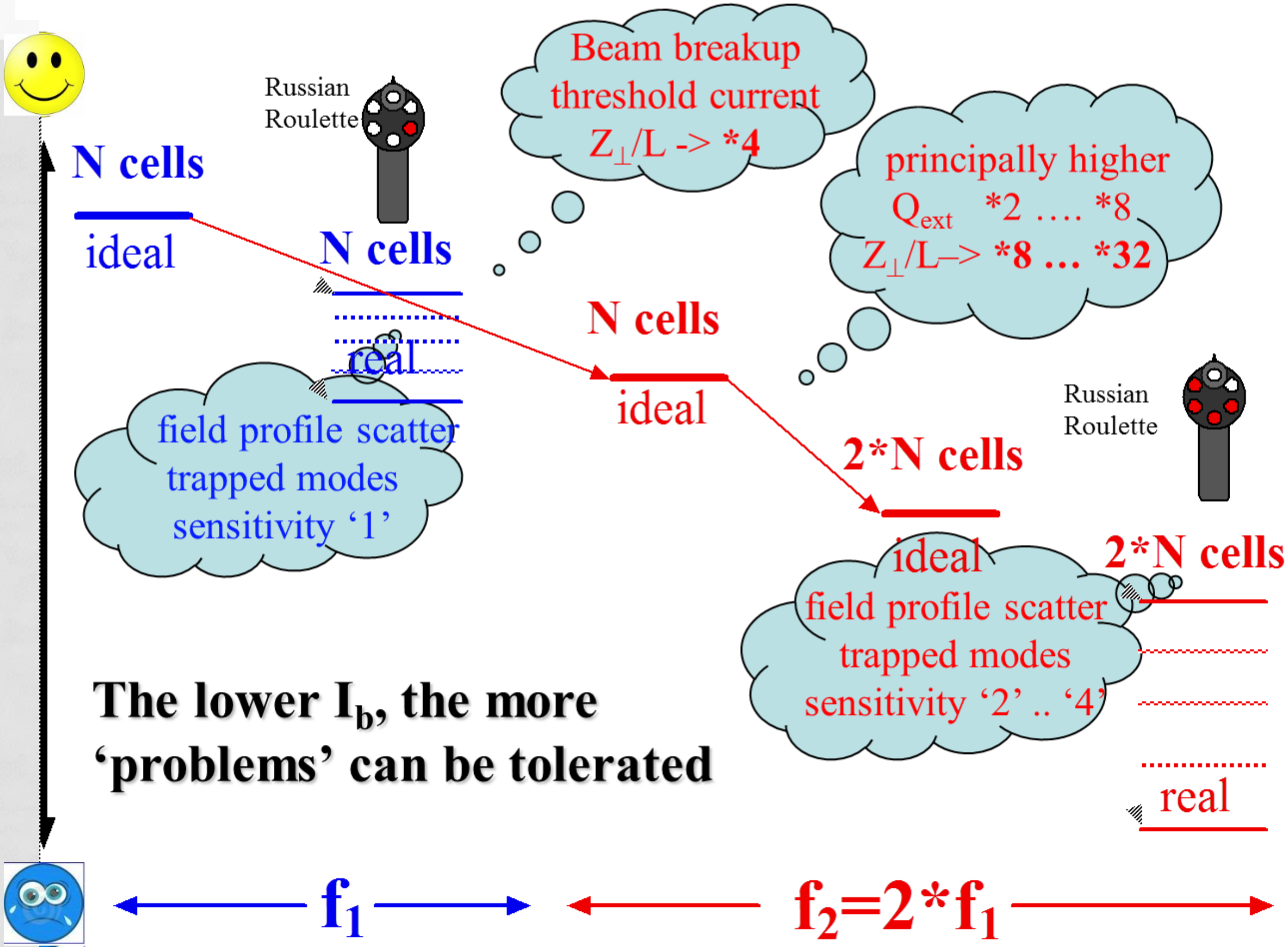
$$\delta \epsilon \propto k_{trans} Q$$

$$k_{(trans)} \propto \frac{1}{R_{iris}^3} \sqrt{d\, \sigma_z N_c}$$



Limit, max current → instabilities

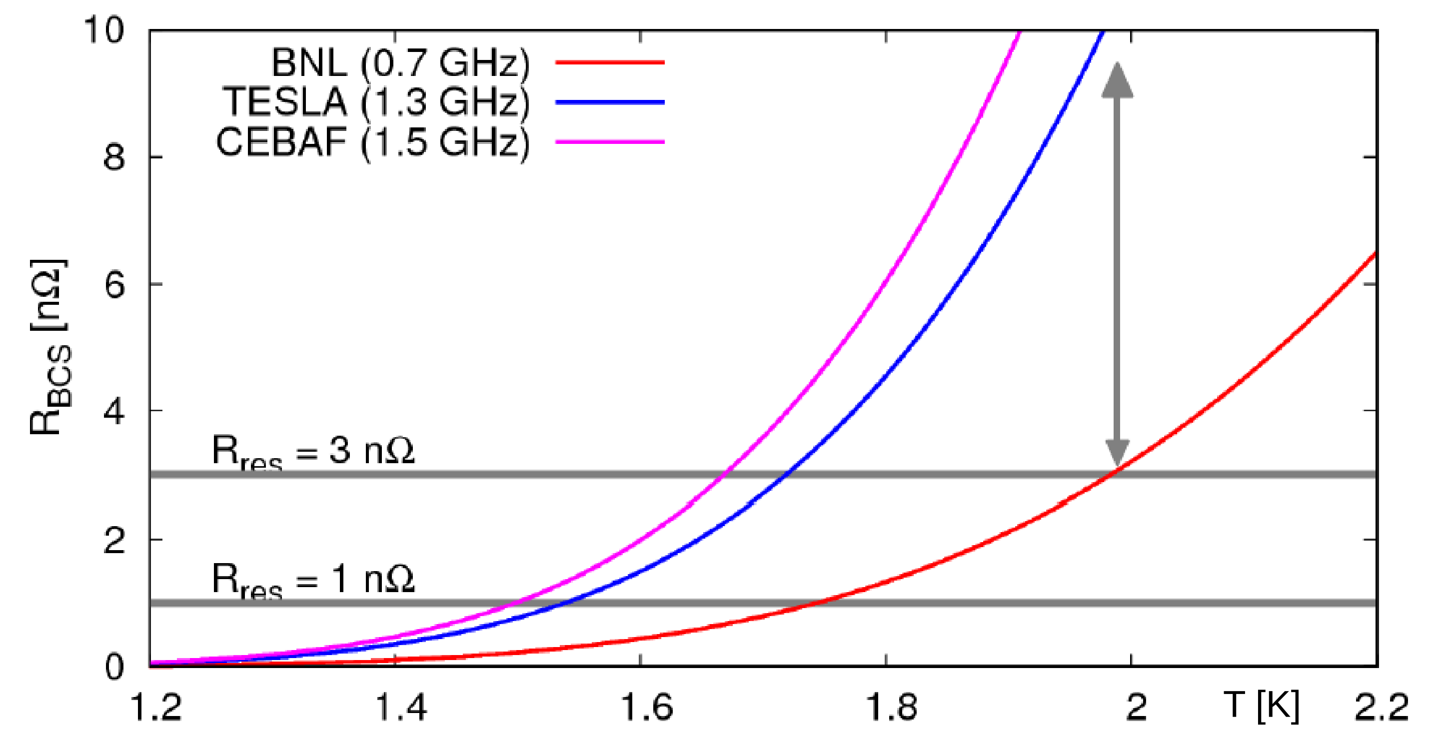
Which frequency?



J. Tückmantel: SPS RF Choice, SPL-f-review 2008

Dynamic wall losses

$R_s = R_{BCS} + R_{res}$

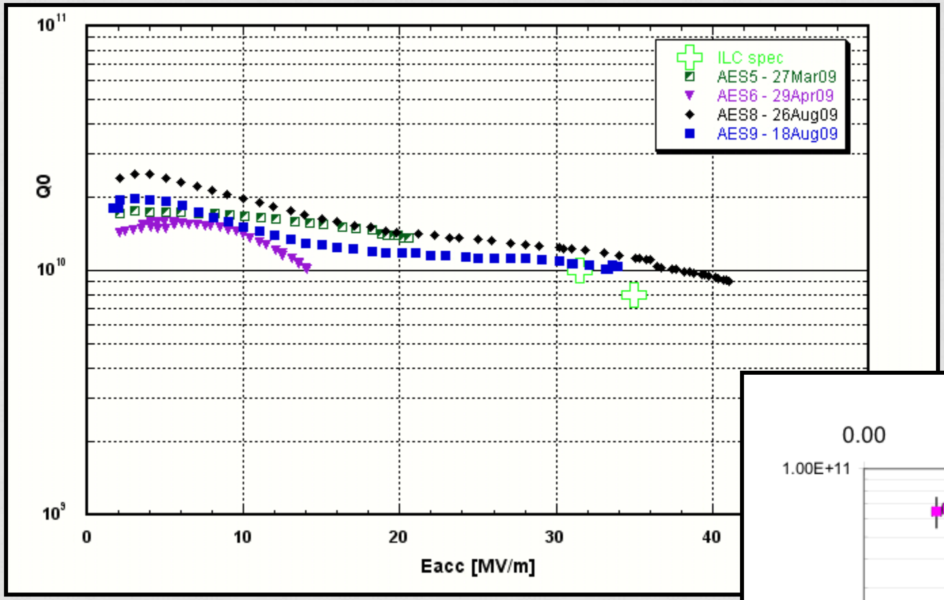


R. Calaga

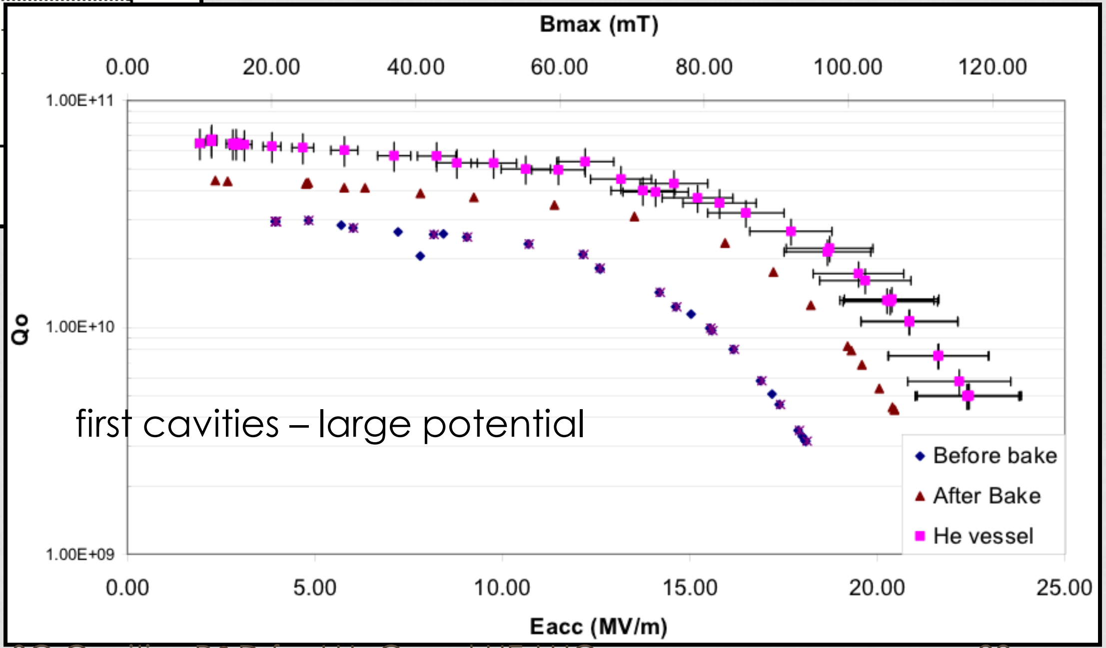
For small R_{res}, this clearly favours smaller f.

Cavity performance today

ILC Cavities 1.3 GHz, BCP + EP (R. Geng SRF2009)



BNL 704 MHz test cavity, BCP only!
(A. Burill, AP Note 376)



first cavities – large potential

HOM Power

- For σ_z = 2 mm, one gets:

Frequency	k_L (V/pC)	k_T (V/pC/m)
700 MHz	2.64	2.46
1300 MHz	8.19	28.1

- For 6.6 mA, the total current is 40 mA (6 passages), resulting in an average HOM power $k_L \cdot Q \cdot I_{beam}$ of:

For 1300 MHz $\rightarrow$ 105 W per cavity

For 700 MHz $\rightarrow$ 33 W per cavity

The bunch length is much smaller – so expect even more HOM power!

Power consumption estimates (rough)

	Units	721.4 MHz	1322.6 MHz
Main linacs (no beam loading)			
R/Q	[Ω]	500	1036
Q_0 @ 2 K		2.4 x 10^{10}	1 x 10^{10}
V/cavity	[MV]	20.8	20.8
P_{RF}/cavity	[kW]	43.4	20.9
n_{cav}		960	960
total RF power	[MW]	41.7	20.1
P_{AC}	[MW]	**59.6**	**36.5**
Synchrotron radiation compensation			
total RF power	[MW]	12.4	
P_{AC}	[MW]	**20.7**	
Heat load (assuming Q_0 @ 2 K, conversion factor 600)			
P_{AC}/cav	[kW]	21.25	24.2
$P_{cryo,\ AC}$	[MW]	**20.4**	**23.2**
HOM's	[MW]	**0.75**	**2.34**
Static, coupler, interconnects	[MW]	**3**	**3**
0.3 GeV injector			
P_{AC}	[MW]	**5**	
Total P_{AC}	**[MW]**	**109.5*)**	**90.74**

Assuming $Q_{ext} = 10^7$

Can this be recovered?

η = 60% assumed

preliminary – needs x-check!

*) **78.6** with adapted Q_{ext}

ERL Choice of frequency

- The frequency has to be a harmonic of 20.04 MHz!
- LHeC baseline: 721.42 MHz, alternative 1322.6 MHz.
- **Advantages of lower frequency:**
  - Less cryo-power
  - High-power couplers easier
  - Less cells per cavity – less trapped modes
  - Less beam loading and transverse wake – better beam stability
  - Less HOM power
  - Synergy with SPL, e-RHIC and ESS.
- **Advantages of higher frequency:**
  - Larger R/Q → with same Q_{ext} less RF power (but Q_{ext} must be reduced!)
  - Synergy with ILC/X-FEL

LHeC: Some references

1. LHeC Draft CDR: http://cdsweb.cern.ch/record/1373421
2. F. Zimmermann LHeC LR option, UPHUK-4
3. ILC RDR: http://www.linearcollider.org/about/Publications/Reference-Design-Report
4. I. Ben-Zvi et al.: BNL ERL project
5. G. Hofstaetter et al., Cornell ERL project
6. M. Liepe, ERL 2009
7. D. Schulte: TTC meeting Beijing, Dec. 2011
8. cern.ch/lhec

HE-LHC

… NOT MUCH REALLY

References: EuCARD – HE-LHC'10 AccNet mini-workshop, Malta, 2010:
https://indico.cern.ch/conferenceTimeTable.py?confId=97971#all.detailed
HE-LHC parameters: http://cdsweb.cern.ch/record/1373967 (2011)
Landau system: T. Linnecar and E. Shaposhnikova: LHC Project-note-394, 2007

HE-LHC: Longitudinal beam parameters &RF system

HE-LHC: LHC at higher energy: (7 TeV → 16.5 TeV)

- For constant RF voltage bucket area is increasing with beam energy as $E^{1/2}$ => less voltage is required at higher energy.
- To have the same Landau damping at 16.5 TeV as at 7 TeV longitudinal emittance should be also increased as $E^{1/2}$ (from 2.5 eVs to 3.8 eVs). For the same voltage (**16 MV**) this gives the same bunch length: 1.08 ns. **No need for more voltage**.
- Continuous longitudinal emittance blow-up with band limited noise can be considered in coast to avoid emittance decrease due to relatively fast **SR damping**.
- Higher harmonic RF system (800 MHz) can be considered for much shorter (smaller) bunches (< 2 eVs) or for different bunch shapes ("flat", …). Impact on LLRF complexity!

also for LHC!

E. Shaposhnikova

HE-LHC: Beam and RF parameters

E. Shaposhnikova

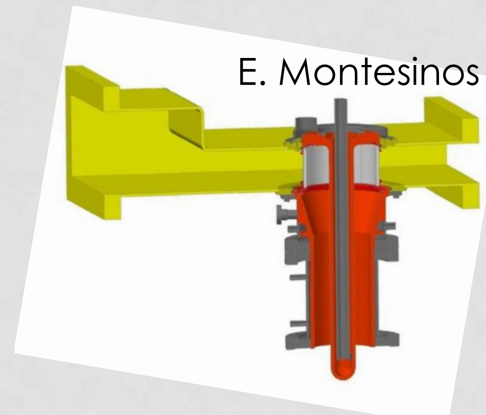
		nominal LHC	HE-LHC
Energy	TeV	7.0	16.5
Bunch spacing	ns	25	50
Bunch population	10^{11}	1.15	1.3
Beam current	A	0.584	0.328
RF voltage/beam @400.8 MHz	MV	16.0	**16.0**
Bunch length (4 sigma)	ns	1.08	1.08
Longitudinal emittance (2 sigma)	eVs	2.5	4.0
Longitudinal emittance damping time	h	13.0	1.0
SR energy loss per turn	keV	6.7	202
Bucket area	eVs	7.9	12.2
Synchrotron frequency	Hz	23.0	14.9

Some initial design thoughts

L. Ficcadenti, J. Tückmantel, R. Calaga

Fundamental Mode:

- Optimize cell geometry, length & aperture (Surface fields, *R*/*Q* etc..)
- Close attention to wall angle (α) to avoid very stiff cavity for freq tuning (800 MHz cavity is twice smaller)



Power coupler:

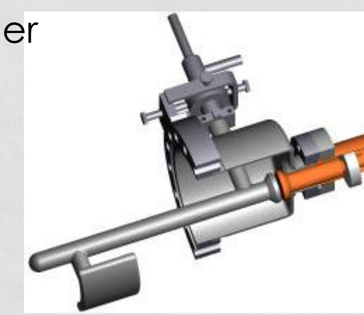
- LHC like coupler, but preferably non-variable
- Approx 100-200 kW (SPL like design)
- needs verification

HOMs:

- Mode separation of the first 2 dipole modes (w.r.t to 800 MHz) (TE_{111} ~ 1 GHz & TM_{110} ~1.1 GHz)
- Scale 400 MHz HOM couplers from LHC (narrow-band & broadband)

CERN/SACLAY Coupler

Narrow band (Main RF)



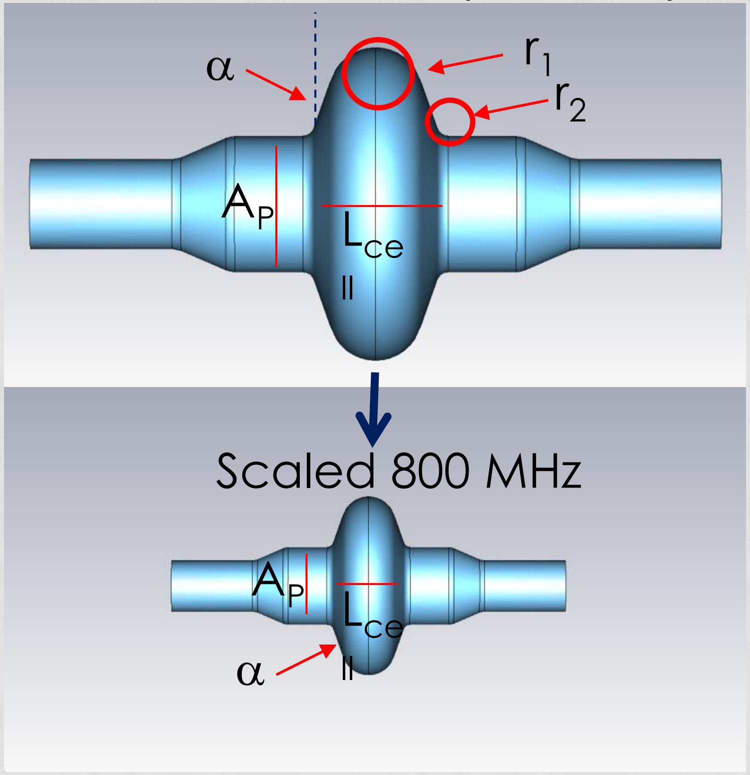
Broadband (HOM)

800 MHz LHC (or HE-LHC) Landau Cavity

f	400 MHz	800 MHz
L_{CELL}	320	~160
A_p	300	150
α	11^0	$< 11^0$
R_1	104	52
R_2	25	12.5

f	[MHz]	400	800
V	[MV]	2.0	2.0
R/Q	[Ω]	44	45.5
E_{pk}	[MV/m]	11.8	29.2
B_{pk}	[mT]	27.3	56.4

LHC Main RF (400 MHz)



L. Ficcadenti, J. Tückmantel, R. Calaga

Summary

- There are challenging subjects ahead to be studied to progress in Superconducting RF!
- LHeC has a substantial RF system for both RR and LR Options; the most interesting and challenging is the high current, high energy Energy Recovery Linac.
- A number of issues (in particular the limits for beam stability) seem to favour 700 over 1300 MHz.
- The HE-LHC RF system is not any harder than the present LHC RF system.
- An initial study on a new RF system for 800 MHz (both for LHC or HE-LHC) has started.

Spare slides

LHeC Frequency choice

- For 6 equally spaced bunches in 50 ns, the bunch spacing should be 8.316 ns $(120.237\text{ MHz})^{-1}$.
- To have every other bunch in a decelerating phase, this bunch spacing must correspond to $(n+1/2)$ RF periods; this results in possible frequencies $f = (n+1/2) \cdot 120.237$ MHz, e.g.:

661.3 MHz, 781.54 MHz, 901. 78 MHz, 1.022 GHz, 1.262 GHz, 1.383 GHz

- For SR loss compensation, all 6 bunches should be in a accelerating phase, i.e. $f = n \cdot 120.237$ MHz, e.g.:

721.42 MHz, 841.66 MHz, 961.9 MHz, 1.082 GHz, 1.202 GHz, 1.322 GHz

- It should be possible to adjust the arc lengths to use an RF at any harmonic of 20.0395 MHz, including e.g. 701.38 MHz and 1.302 GHz.