FCC Week 2015, Washington DC
23-27 March 2015
Marriott Georgetown Hotel
https://indico.cern.ch/event/340703/

FCC RF Overview

Erk Jensen, CERN

… presenting – and gratefully acknowledging – the ideas and contributions of many!

23-March-2015

Outline

- Introduction – what are we talking about?
- High efficiency RF power generation
- Superconducting RF R&D
  - Recent progress
  - The focus of FCC SRF R&D
  - The challenges (power, HOM power)
  - How this fits in with other studies/projects @ CERN
- Standing invitation to join in!

Introduction

- I will be only introducing the subject and sketch the context – no details
- Advertisement: *Please come to tomorrow's dedicated sessions*:

AM: SRF: Novel Cavity Concepts & Cryomodules

	Scenarios and challenges for FCC-ee	*Andrew BUTTERWORTH*	*ROOM C, Marriott Georgetown Hotel*	08:30 - 08:50
09:00	**A compact, modular cryomodule concept suitable for a range of applications and for industrial production**	*Robert RIMMER*		
	Assembly experience of large scale production CM for different applications	*Olivier NAPOLY*	*ROOM C, Marriott Georgetown Hotel*	09:10 - 09:30
	Performance results from elliptical cavities	*Eckhard ELSEN*	*ROOM C, Marriott Georgetown Hotel*	09:30 - 09:50
	Preliminary design of the CEPC SRF system	*Jiyuan ZHAI*		
	Coffee break		*Marriott Georgetown Hotel*	09:50 - 10:30
10:00	**Coffee Break**		*Marriott Georgetown Hotel*	10:00 - 10:30
	Cavity fabrication concepts: rapid forming	*Enzo PALMIERI*	*ROOM C, Marriott Georgetown Hotel*	10:30 - 10:50
11:00	**Fundamental power couplers**	*Eric MONTESINOS*	*ROOM C, Marriott Georgetown Hotel*	10:50 - 11:10
	Advances and perspectives in SRF bulk NB developments	*Oliver KUGELER*	*ROOM C, Marriott Georgetown Hotel*	11:10 - 11:30
	Highly HOM-damped cavities	*Sergey BELOMESTNYKH*	*ROOM C, Marriott Georgetown Hotel*	11:30 - 11:50
	Past, present and future prospects of SRF ingot niobium technology	*Ganapati MYNENI*	*ROOM C, Marriott Georgetown Hotel*	11:50 - 12:00

PM: SRF: Coating Technologies, Higher Efficiency RF

	Ultraefficient superconducting RF cavities for FCC	*Alexander ROMANENKO*	*ROOM C, Marriott Georgetown Hotel*	13:30 - 13:40
	Advances in development of Nb coating technology	*Anne-Marie VALENTE*	*ROOM C, Marriott Georgetown Hotel*	13:40 - 14:00
14:00	**Perspectives of SRF performance of Nb coatings**	*Sarah AULL*	*ROOM C, Marriott Georgetown Hotel*	14:00 - 14:20
	Advances in development of diffused Nb3Sn cavities	*Matthias LIEPE*	*ROOM C, Marriott Georgetown Hotel*	14:20 - 14:40
	Development of non-Nb coatings	*Alexander GUREVICH*	*ROOM C, Marriott Georgetown Hotel*	14:40 - 15:00
15:00	**Thin films SRF studies in AS...**	*Reza VALIZADEH*		
	Coffee break		*Marriott Georgetown Hotel*	
	Coffee Break		*Marriott Georgetown Hotel*	
	Coffee Break		*Marriott Georgetown Hotel*	
	High power solid state amplifiers technology – start of the art, advances & perspectives	*Georgy SHARKOV*		
16:00	**Development of klystrons with ultimately high - 90% RF power production efficiency**	*Christopher LINGWOOD*		
	High power IOTs	*Morten JENSEN*	*ROOM C, Marriott Georgetown Hotel*	16:30 - 17:00

FCC-ee and FCC-hh

- **FCC-ee** (45 GeV … 175 GeV electrons and positrons):
  - Total RF power 100 MW CW!
  - Requires R&D for
    - Highly efficient RF power generation
    - An RF system scalable to this size (11 GV)
    - An RF system that can cope with 1.4 A beam current
    - Optimum use of cryogenic system

SC Cavities
Cryomodules
Amplifiers
Power Couplers
HOM Damping

FCC-ee is considered as intermediate stage before FCC-hh!

- **FCC-hh** (50 TeV protons):
  - A "small" RF system in comparison (about 2x LHC)
  - … will however take advantage of R&D for FCC-ee
  - Challenging beam dynamics! (beam-beam, e-cloud, impedances and their reduction…) → dedicated session "FCC-hh Technology and beam physics"

… a 100 MW CW class SRF system requires R&D for

HIGH EFFICIENCY RF POWER GENERATION

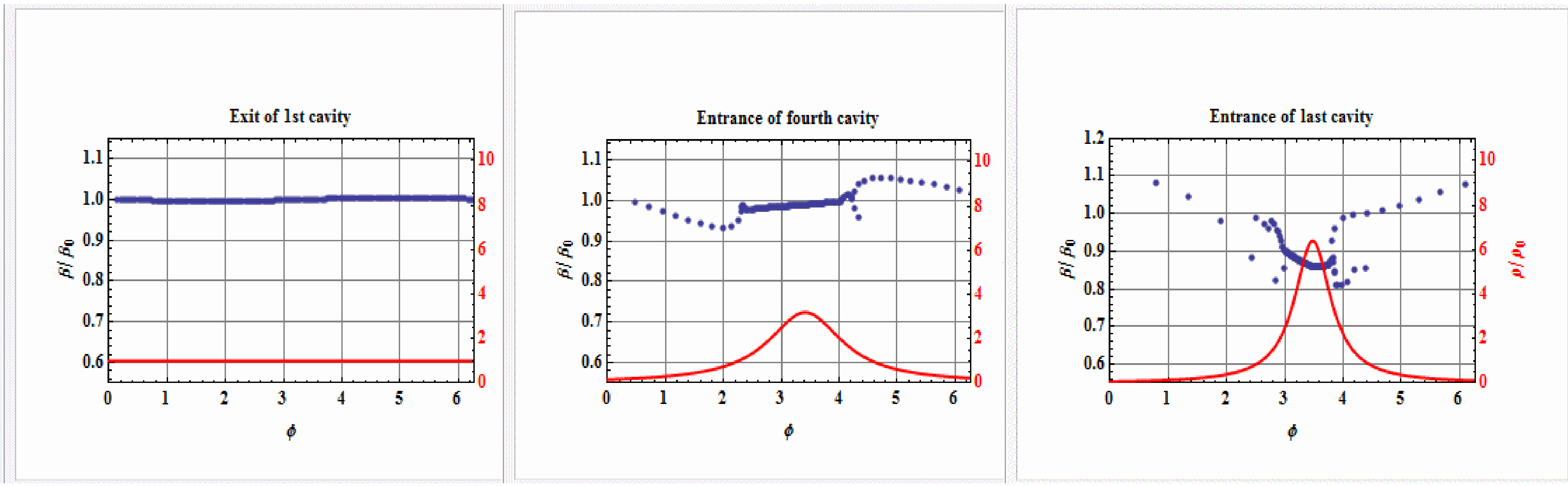
Synergy with EuCARD II, WP “EnEfficient”, Co-funded by the European Commission, Grant Agreement No: 312453

High efficiency klystrons

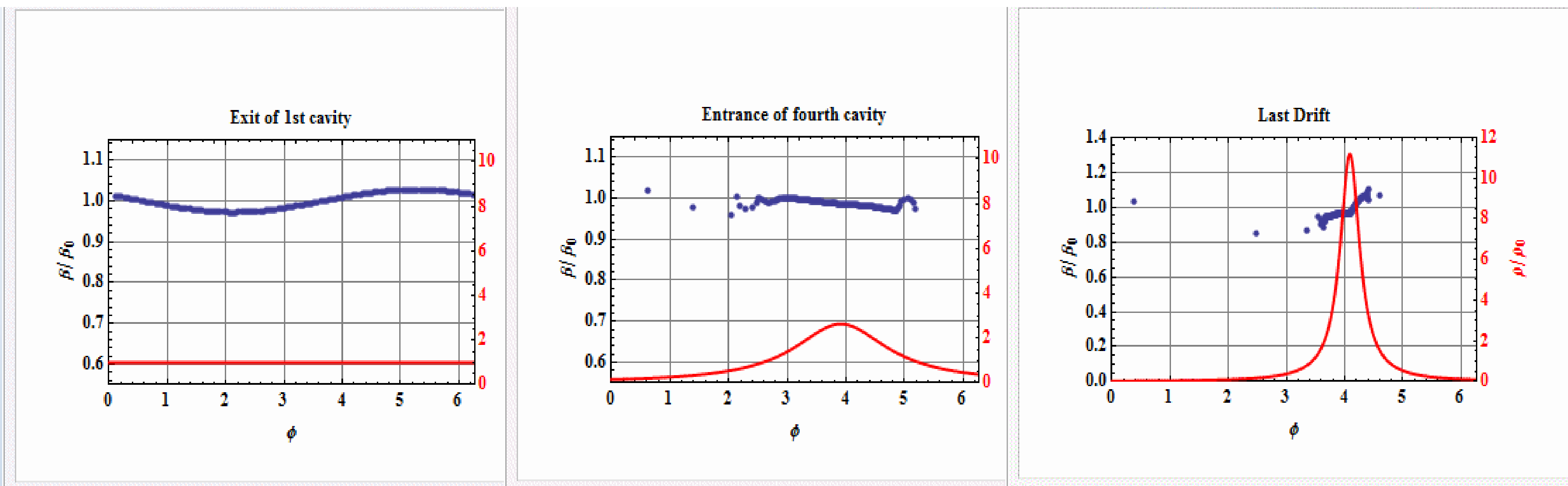
Tomorrow afternoon: C.Lingwood's presentation

- State-of-the-art klystrons reach about 65% efficiency at saturation, normally they are used below saturation for amplitude control.
- 2014 saw a breakthrough in klystron theory:
- The "**congregated bunch**" concept was re-introduced [V.A. Kochetova, 1981]
  - (later electrons faster when entering the output cavity).
- The concept of "**bunch core oscillations**" was introduced [A. Yu. Baikov, et al.: "Simulation of conditions for the maximal efficiency of decimeter-wave klystrons", Technical Physics, 2014]
  - (controlled periodic velocity modulation)
- The "**BAC**" method was invented [I.A. Guzilov, O.Yu. Maslennikov, A.V. Konnov, "*A way to increase the efficiency of klystrons*", IVEC 2013]
  - (Bunch, Align velocities, Collect outsiders)
- These methods together promise a significant increase in klystron efficiency (approaching 90%)
- An international collaboration has started – prototypes are being designed. (SLAC plans to convert an existing 5045 klystron – simulations are encouraging)

20 MW, 8 beams 5 cavities MBK originally simulated by Chiara Marrelli



20 MW, 8 beams 5 cavities MBK with 'core oscillations' simulated by Andrey Baikov



Slides from I. Syratchev, https://indico.cern.ch/event/297025/contribution/2 at "EnEfficient RF Sources" Workshop, Daresbury 2014

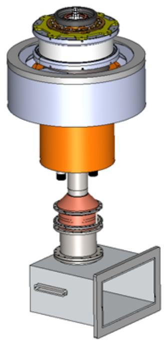
ESS approach: Multi-beam IOTs

M. Lindroos: ESS project status, SLHiPP-5, 18-19 March,2015

WP8 1.2 MW IOT Prototype Update

Current Status:

- Two contracts place in September 2014
- One contract with Thales/CPI
- One contract with L3
- Delivery in 24 months
- Factory Acceptance at L3 and CERN
- Kick-off meetings and one Preliminary Design Report approved

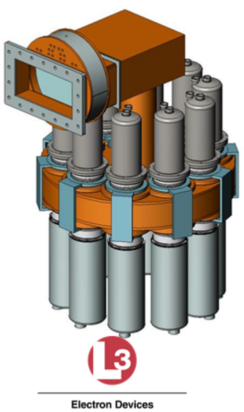


Pre-tender CPI Cartoon

Next stages:

- Single beam IOTs/beam sticks being developed by both suppliers
- Complete thermal, mechanical and RF modelling
- Complete Preliminary and Final Design Reviews
- Identify auxiliary supplies: Ion pumps, solenoid, filament
- Identify RF drivers (up to 2 kW)

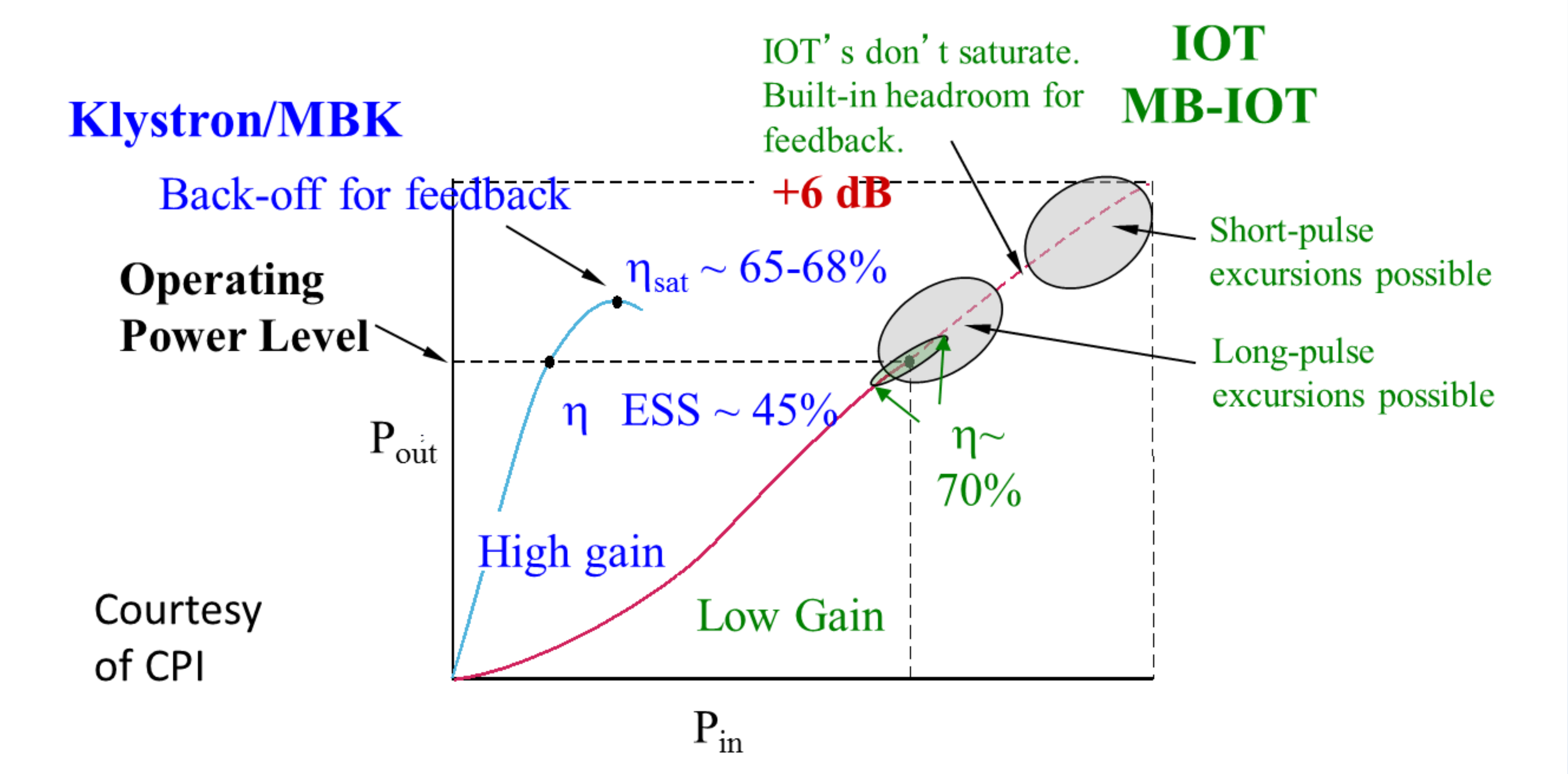
Parameter		Comment
Frequency	**704.42 MHz**	**Bandwidth > +/- 0.5 MHz**
Maximum Power	**1.2 MW**	**Average power during the pulse**
RF Pulse length	Up to 3.5 ms	Beam pulse 2.86 ms
Duty factor	Up to 5%	Pulse rep. frequency fixed to 14 Hz
Efficiency	Target > 65%	



Differences IOT-klystron

→ Tomorrow afternoon: M. Jensen's presentation

M. Jensen: IOTs for ESS, EnEfficient RF Sources RF Workshop, 2014, https://indico.cern.ch/event/297025/contribution/11



… a 100 MW CW class SRF system – 11 GV of RF and to cope with 1.4 A beam requires

SUPERCONDUCTING RF R&D

Complication: FCC-ee is 4 different machines!

- RF: 800 MHz, 400 MHz or a combination

FCC-ee (per beam)	*Z*	*W*	*H*	*tt*
Energy [GeV]	*45*	*80*	*120*	*175*
Beam current [mA]	*1450*	*152*	*30*	*6.6*
SR power [MW]	*50*	*50*	*50*	*50*
Energy loss/turn [MeV]	*30*	*330*	*1,670*	*7,550*
RF voltage [MV]	*2,500*	*4,000*	*5,500*	*11,000*

- For comparison: FCC-hh (400 MHz)

FCC-hh (per beam)	*50* TeV
Energy [GeV]	*50,000*
Beam current [mA]	*510*
SR power [MW]	*2.4*
Energy loss/turn [MeV]	*4.6*
RF voltage [MV]	*32*

SRF R&D around the world – recent progress

- 2013 saw two **major breakthroughs** in SRF R&D:
  1. Anna Grasselino et al. (FNAL): "New Insights on the Physics of RF Surface Resistance and a Cure for the Medium Field Q-Slope", SRF 2013
  2. Sam Posen et al. (Cornell): "Theoretical Field Limits for Multi-Layer Superconductors", SRF 2013

This is encouraging and highly motivating!

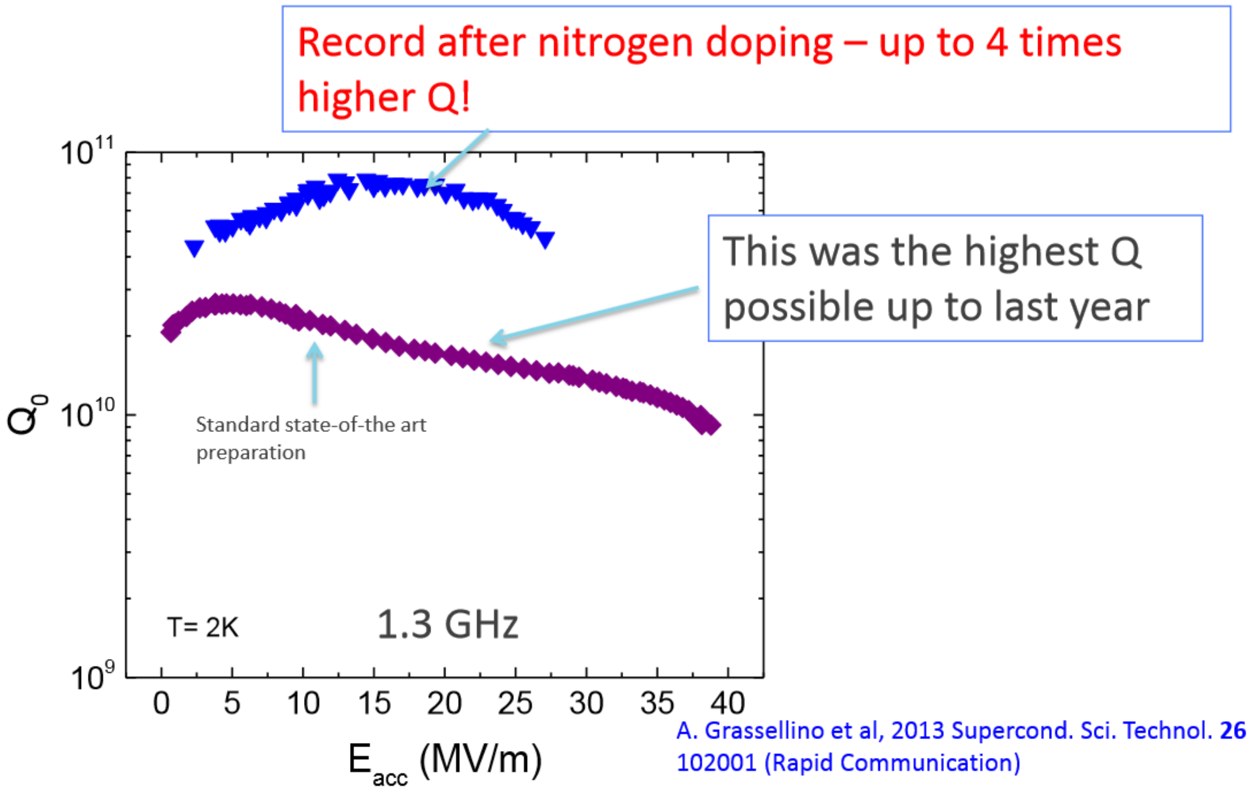
R&D like this is essential to develop and optimize the FCC-ee RF system!

A. Grasselino et al.: Nitrogen Doping

A. Romanenko, "Breakthrough Technology for Very High Quality Factors in SRF Cavities", Linac2014, TUIOC02

→ Tomorrow afternoon: A. Romanenko's presentation

Nitrogen doping: a breakthrough in Q



A. Grassellino et al, 2013 Supercond. Sci. Technol. **26** 102001 (Rapid Communication)

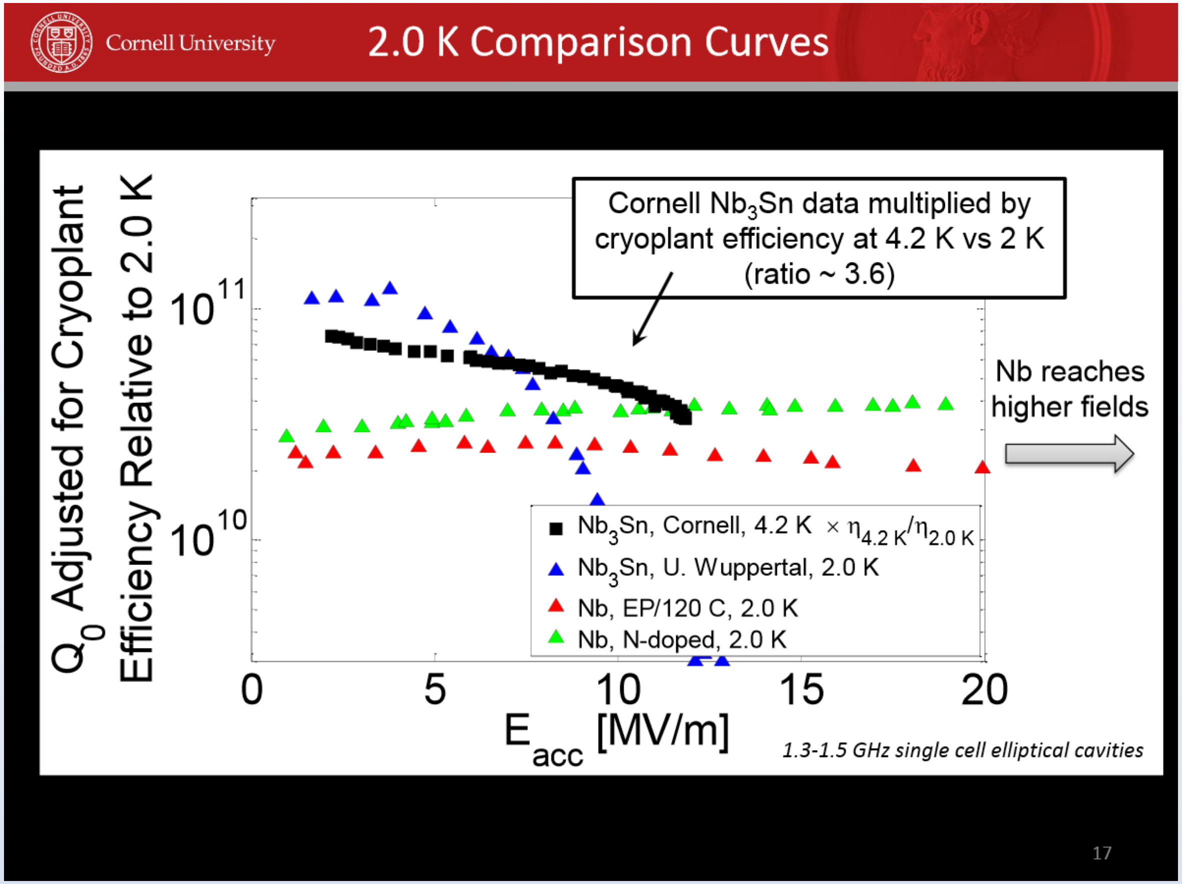
Fermilab

4 Alexander Romanenko | LINAC'2014 2 Sep 2014

Sam Posen et al.: Nb_3Sn coating

→ Tomorrow afternoon: M. Liepe's presentation

S. Posen, "Nb3Sn – Present Status and Potential as an Alternative SRF Material", Linac2014, TUIOC03



- Careful experiment with Nb_3Sn coating (2…3 µm) & 6 h annealing resulted in $Q_0 > 10^{10}$ with modest Q-slope, even at 4.2 K!
- The cryogenic efficiency at 4.2 K is a factor 3.6 better than at 2 K.
- Concerning power needed to cool dynamic losses, this cavity outperforms Nb cavities.

- Drawback today: maximum field.

SRF Activities at CERN – in the nineties (LEP)

- At LEP times, CERN had the largest SRF installation

K. Schirm (also featured on the Calendar photo!)

SRF Activities at CERN – today (1/2)

Cavity reception & tuning

HIE-Isolde cavity preparation

HIE-Isolde cavity substrate

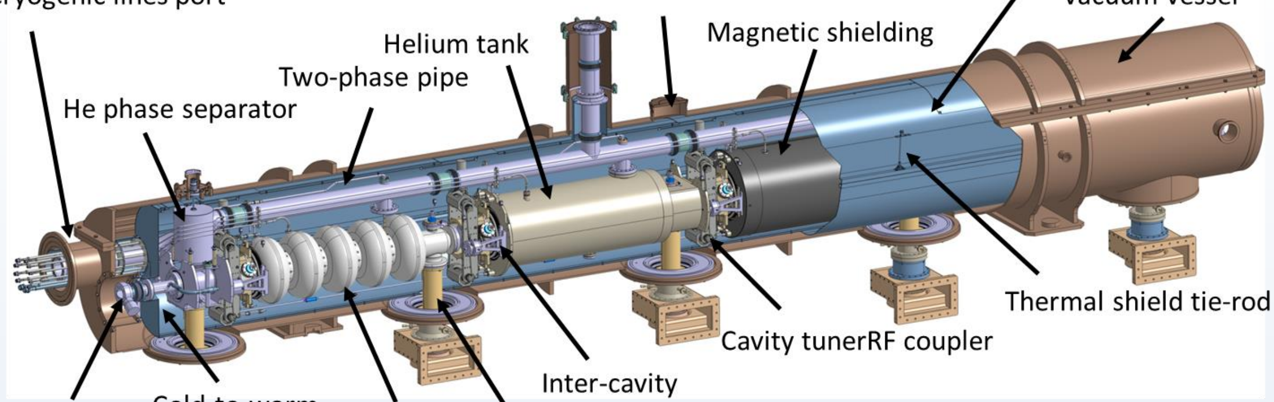
EP

SM18 Upgraded and extended clean rooms with HP water rinsing und UP water station

K. Schirm

HIE-Isolde cavity assembly

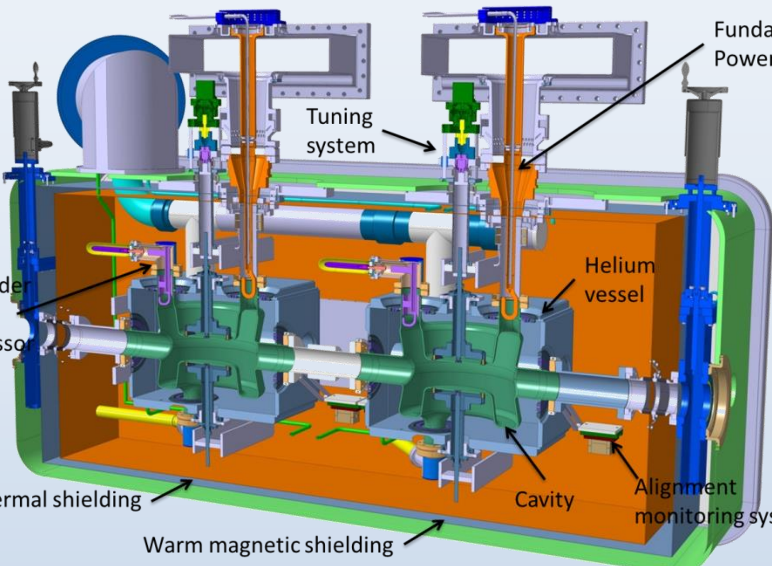
SRF Activities at CERN – today (2/2)



SPL cryomodule, 704 MHz
Novel cavity suspension by FPC, cavities in bulk Nb

O. Capatina et al.

HL-LHC crab cavities, 400 MHz, 2-cavity prototype CM, cavities in bulk Nb (fabricated at Niowave)



SRF activities at CERN

The CERN SRF R&D has to cover many areas, accelerators, technologies.
Where possible, choices were made to exploit synergies!

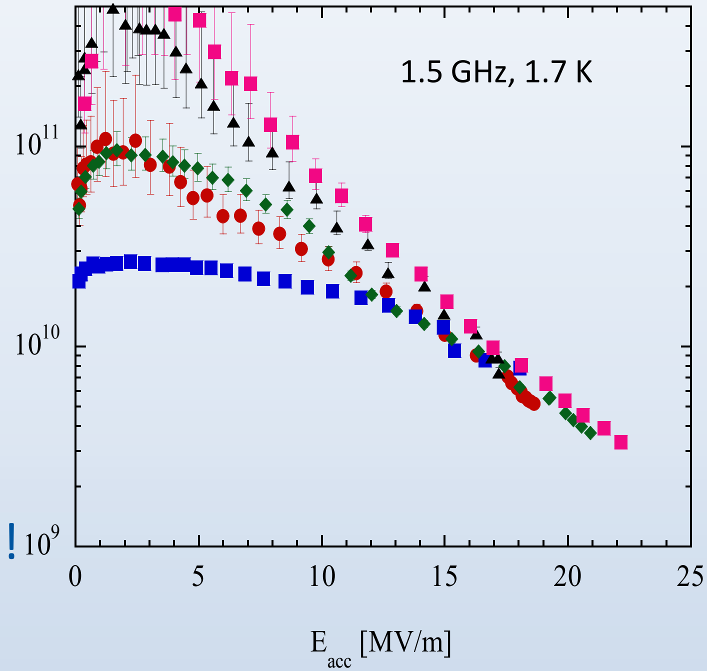
Programme	Frequency (MHz)	Technology
LHC, spare and more	400	Nb on Cu
LHC upgrade	800	Nb on Cu? Bulk?
HIE-ISOLDE	101	Nb on Cu
CRAB	400	Bulk Nb
SPL (ESS)	704	Bulk Nb
ERL-Facility, FCC-he	800	Bulk Nb
FCC-ee, FCC-hh	400 & 800	Nb on Cu & bulk

FCC SRF R&D

→ Tomorrow afternoon: S. Aull's presentation

S. Aull

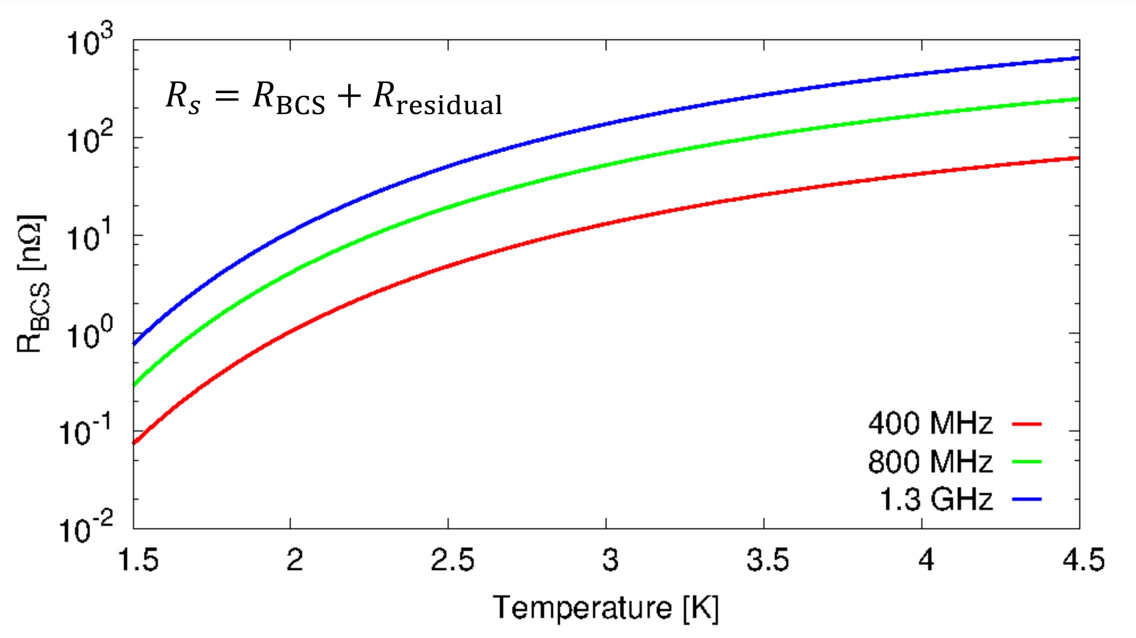
- Past CERN SRF was successfully based on thin film **Nb sputtered on Cu**.
- We believe that this technology has still large potential and wish to concentrate R&D (but not exclusively) on **thin films**.
- Advantages:
  - Substrate (Cu) with good thermal conductivity, easy to machine and work, mechanically and thermally stable, cheaper than Nb.
  - Very large Q_0 was demonstrated at low field.
  - Possible to tune material parameters (RRR) to minimize dissipation
- Disadvantage: Serious Q-slope!
- First goal: Understand Q-slope & find cure!



Courtesy of S. Calatroni

Areas of R&D for FCC-ee

- Cryogenic capacity for CW, minimize static & dynamic heat load
  - Large G (and Q_0), preferably at 4.5 K. ($P_{\mathrm{avg}} = \frac{R_S}{\frac{R}{Q} \cdot G}$)



$R_{\mathrm{BCS}} \propto \omega^2$

R. Calaga

Optimum frequency?

- $R_{BCS} \propto \omega^2$ favours lower f, but $P_{total} \propto \frac{E_{\mathrm{acc}} \cdot R_s(f,T,B)}{f}$ favours lower frequency, where R_s is dominated by R_{residual}.
- There is an optimum f for cryogenic losses!

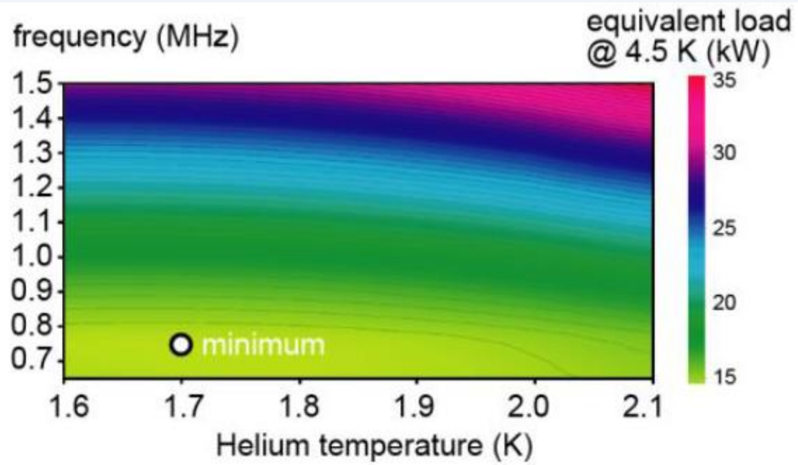


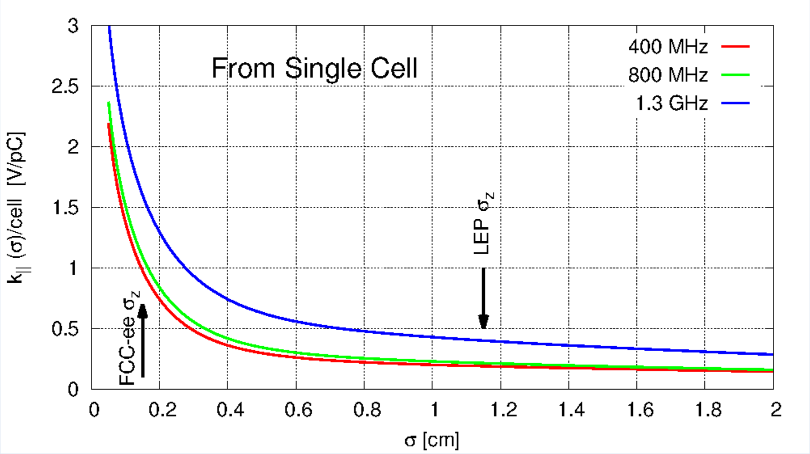
Figure 2: Equivalent dynamic and static losses at 4.5 K for the proton linac covering three β_g-sections (cf. text).

F. Marhauser, Cost Rationales for an SRF Proton Linac, IPAC-14, THPME053

- At high beam current however, HOM power becomes excessive!

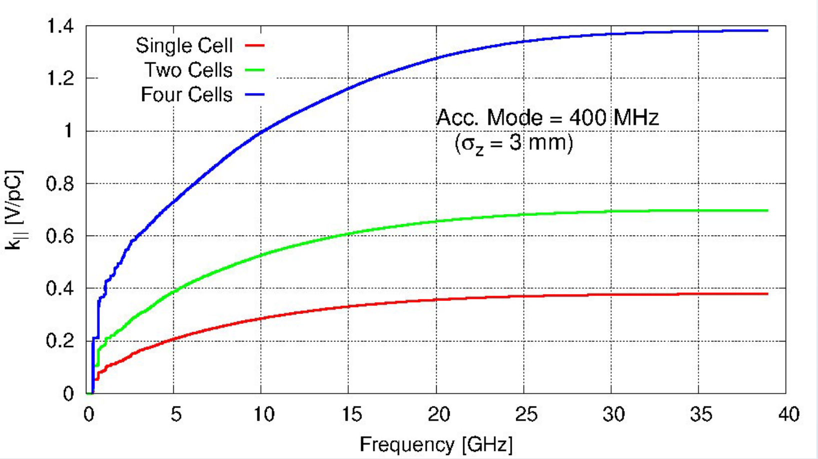
Loss factor vs. bunch length

- $k_{\mathrm{loss}} \propto \frac{1}{r_{\mathrm{iris}}} \sqrt{\frac{l_{\mathrm{gap}}}{\sigma_z}} \sqrt{N_{\mathrm{cell}}}$
- Short bunches → wide spectrum → large HOM power
  $k_{\mathrm{loss}}\, q\, I_{\mathrm{beam}}$, 1 V/pC corresponds to 42 kW of HOM power



R. Calaga

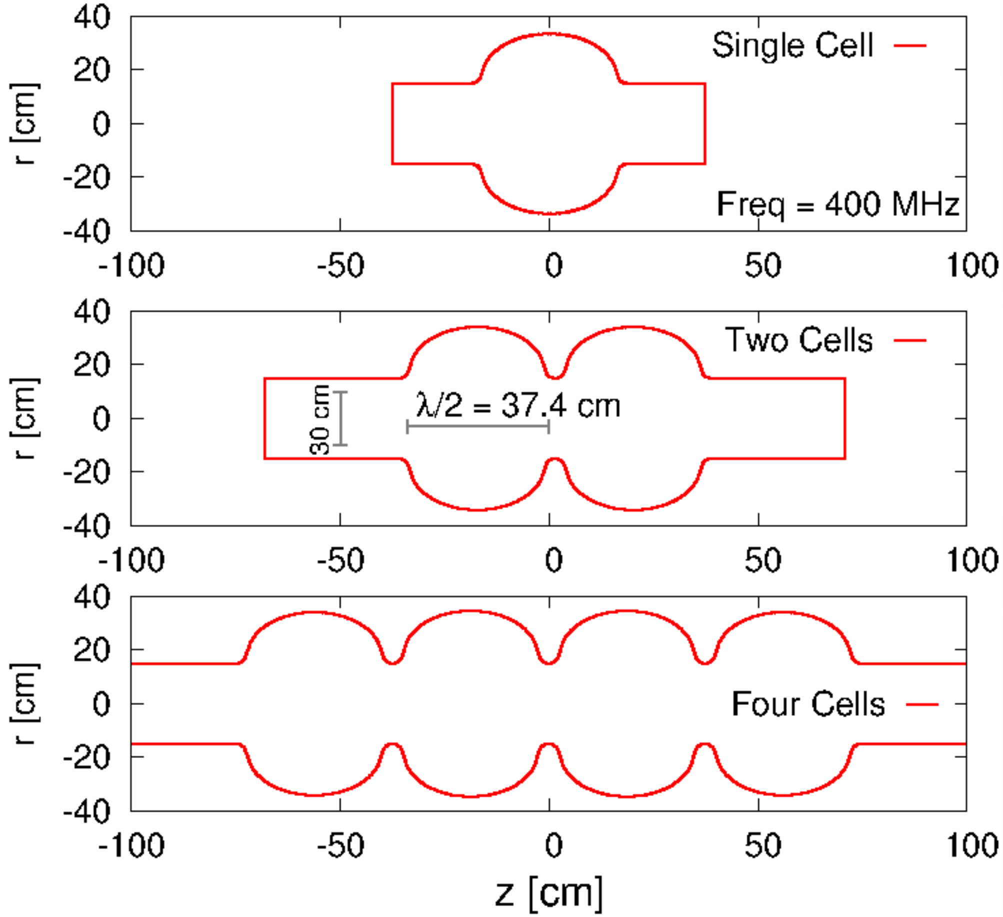
… favours lower frequency



R. Calaga

… favours fewer cells/cavity

Cavity options under study



R. Calaga

l[mm]	V[MV]	$\frac{R}{Q}$ [Ω]
374	3.75	44
748	7.5	84
1500	15	155

Again the FCC-ee parameter table

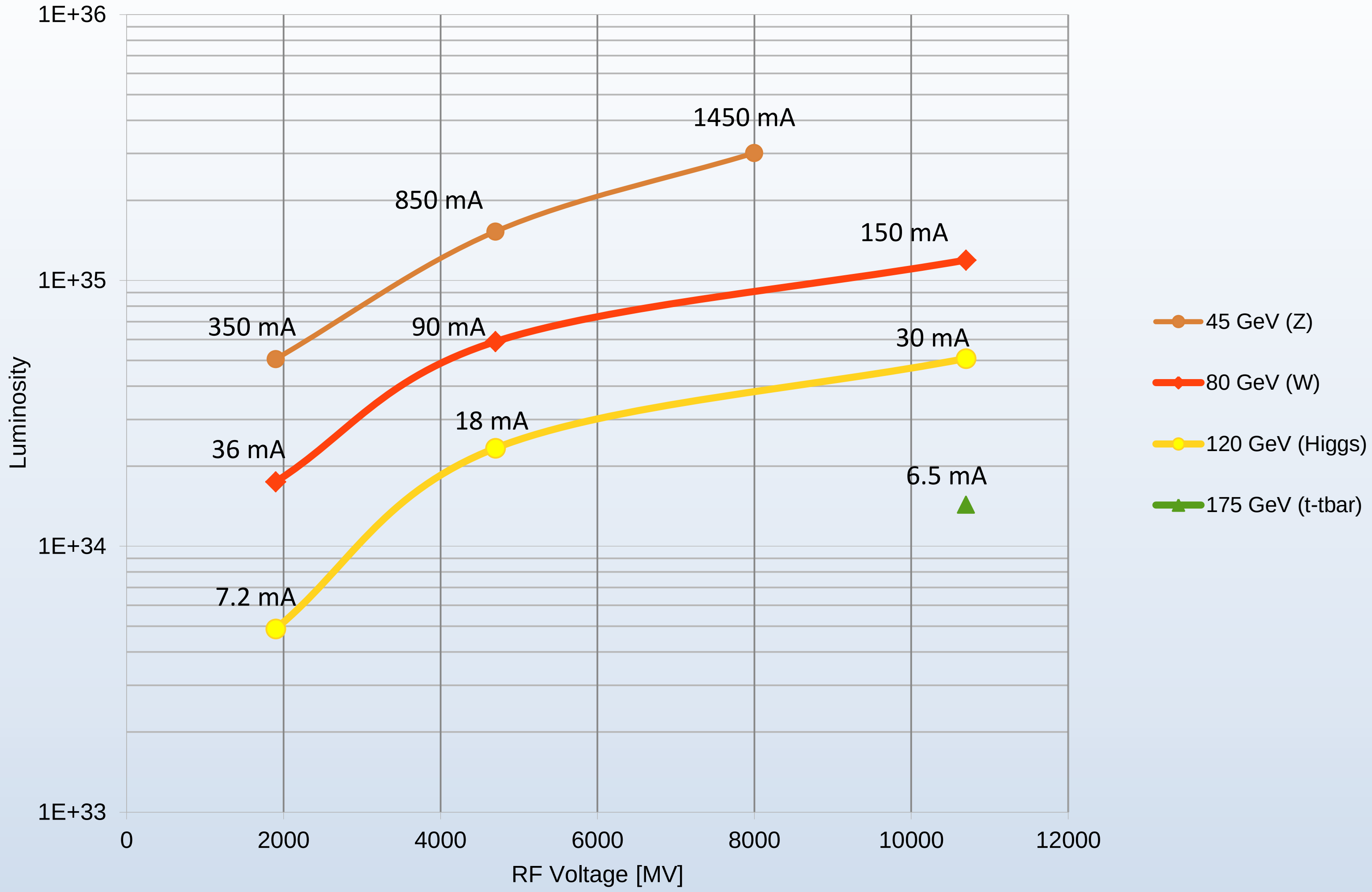
- RF: 800 MHz, 400 MHz or a **combination**

FCC-ee (per beam)	*Z*	*W*	*H*	*tt*
Energy [GeV]	*45*	*80*	*120*	*175*
Beam current [mA]	*1450*	*152*	*30*	*6.6*
SR power [MW]	*50*	*50*	*50*	*50*
Energy loss/turn [MeV]	*30*	*330*	*1,670*	*7,550*
RF voltage [MV]	*2,500*	*4,000*	*5,500*	*11,000*

- Presently considered:
  - 400 MHz base system, compatible with large beam current for Z, W, H
  - … complemented with 800 MHz system with high gradient for tt
  - Share cavities between both beams for high energy (factor 2)

Staging scenarios studied by U. Wienands

→ Wednesday morning: U. Wienands' presentation



Conclusion

- Recent R&D results in both **SRF** and **high-η RF** power are promising and motivating.
- These are exciting times for R&D, and FCC urgently needs R&D in these areas to make it more cost-effective & to perform better!
- – or – : FCC is a unique opportunity to push these technologies!
- There are **strong synergies** with other projects and studies – coordination is needed to optimally exploit these.
- Expertise and experience is distributed around the world – we need international collaboration – we need you! **Please come on board**!

- Thank you very much !

CERN