Linac strategies for the lower beam energies

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TCADS-2 Workshop

Technology and Components of Accelerator Driven Systems
Nantes
May 21st - 23rd, 2013

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Claim

Linacs are the only choice above a certain level of time averaged or pulsed beam current request.

But it is not fixed, where these limits are, and they are depending on the state of the art in a manifold of technologies, like:

RF amplifiers, RF resonators, surface treatment and analysis

Cryotechnology, room temperature cooling technique

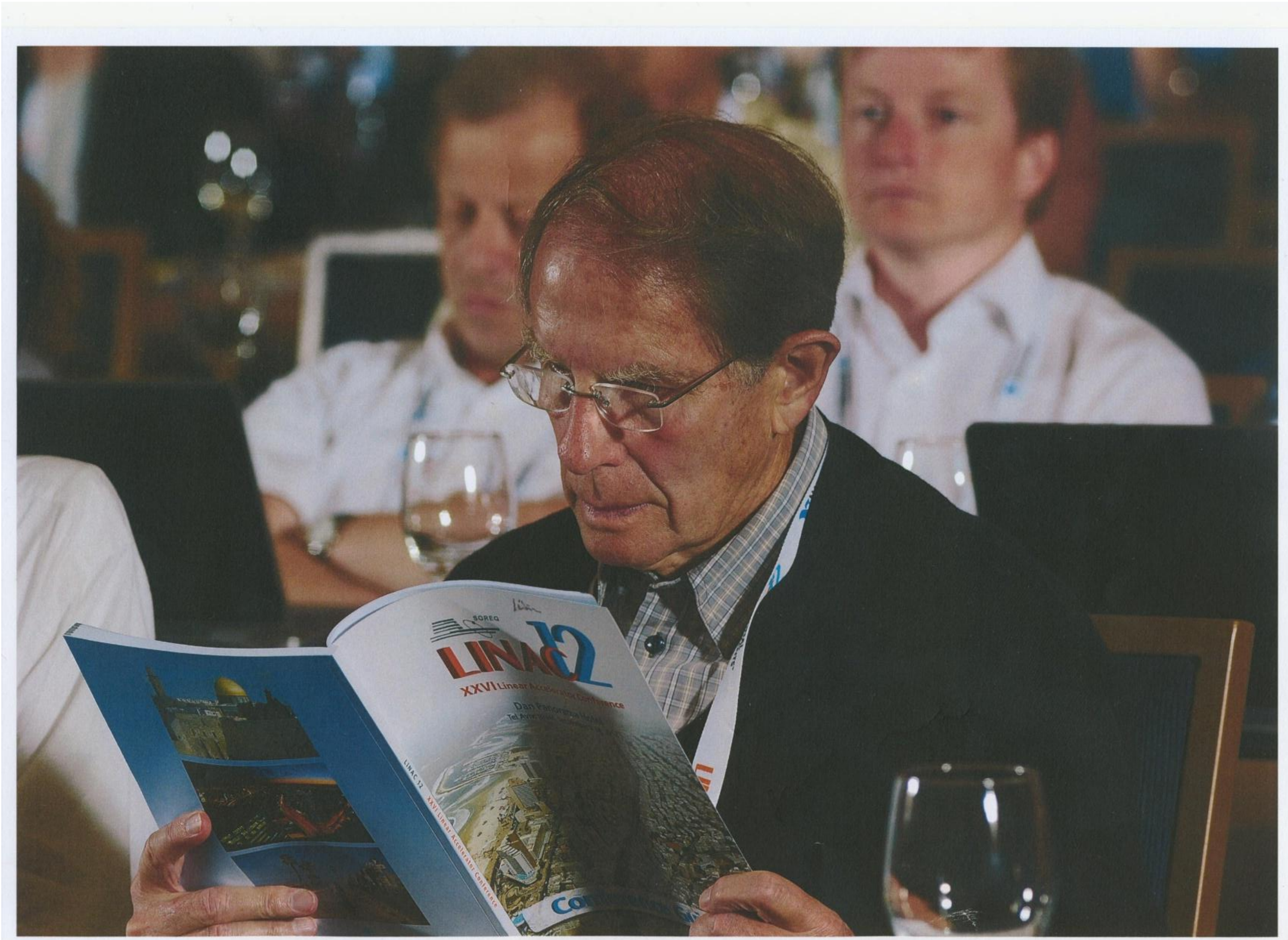
Magnet and vacuum technology

Beam diagnostics, alignment concepts

Ion production and beam formation

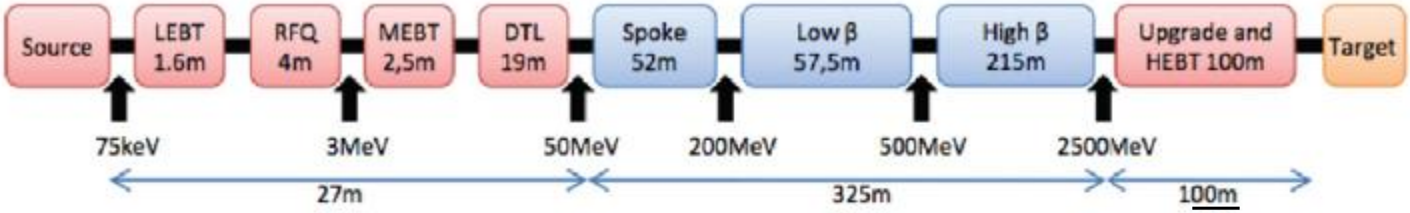
New developments like laser acceleration, plasma wake field acceleraion

In Memoriam Horst Klein



Courtesy of Holger Podlech

Accelerator Concepts



LINAC Example: Concept for the ESS linac. $\overline{E} = 7MV/m$

Electrostatic beam formation and acceleration by rf cavities

100 MHz → 10 GHz

1 MV/m → 25 MV/m

cw operation → pulsed s.c. or r.t.

$\beta \geq 0.01$ → $\beta \approx 1$

Transverse beam focusing by magnetic lenses mostly

Disadvantages of Linacs:

-One dimensional array makes problems in the acquisition of a suited building site, length proportional to end energy

-Very large and expensive rf amplifier installations needed

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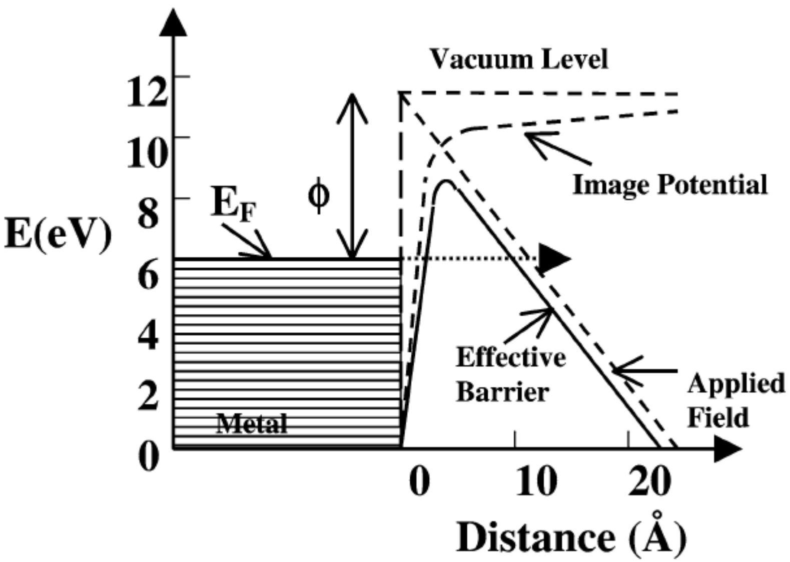
Improved reliability and efficiency of Linacs need

1. Higher acceleration fields
2. Improved rf amplifier technology
3. Superconducting (sc) versus room temperature (rt) technology investigation
4. Adequate beam dynamics and simulations
5. beam loss reduction

These topics will be discussed now

Higher acceleration fields

1. Field limits



Fowler-Nordheim eq. for rf-operation:

$$d(\ln(I_F / E^{2.5}) / d(1/E) = -k / \beta \quad ;$$

$I_F =$ field emission current; $E =$ electric field;

$k = f(\Phi)$; material dependent

$\beta =$ field enhancement factor;

$E_F = \beta \cdot E$;

$E = E_{surf}$ for ideal surfaces

Typical β-range: 100 - 1000

Higher acceleration fields

Kilpatrick criterion for the limiting electric field $E = V/g$, gap width g

$$f = 1.64\,E^2 \cdot e^{\frac{-8.5}{E}} \quad ; \quad E/MV/m \;\; ; \;\; f/MHz$$

f / MHz	E / MV/m
7.5	5
70	10
429	20
2122	40
9438	80
15063	100
22001	120
30250	140

GSI-HSI, 36 MHz too pessimistic (5–10 MV/m)

Fit to experiments (20–80 MV/m)

DESY-Tesla, 1.3 GHz
SLAC

too optimistic (100–140 MV/m)
CERN CLIC-TF

Higher acceleration fields, SC Cavities

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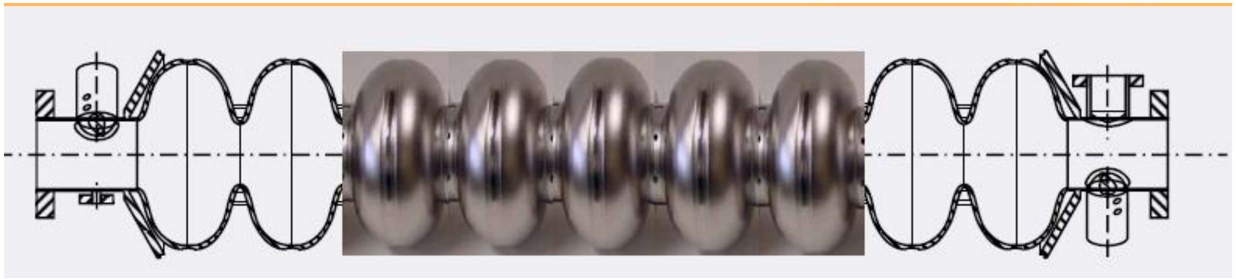
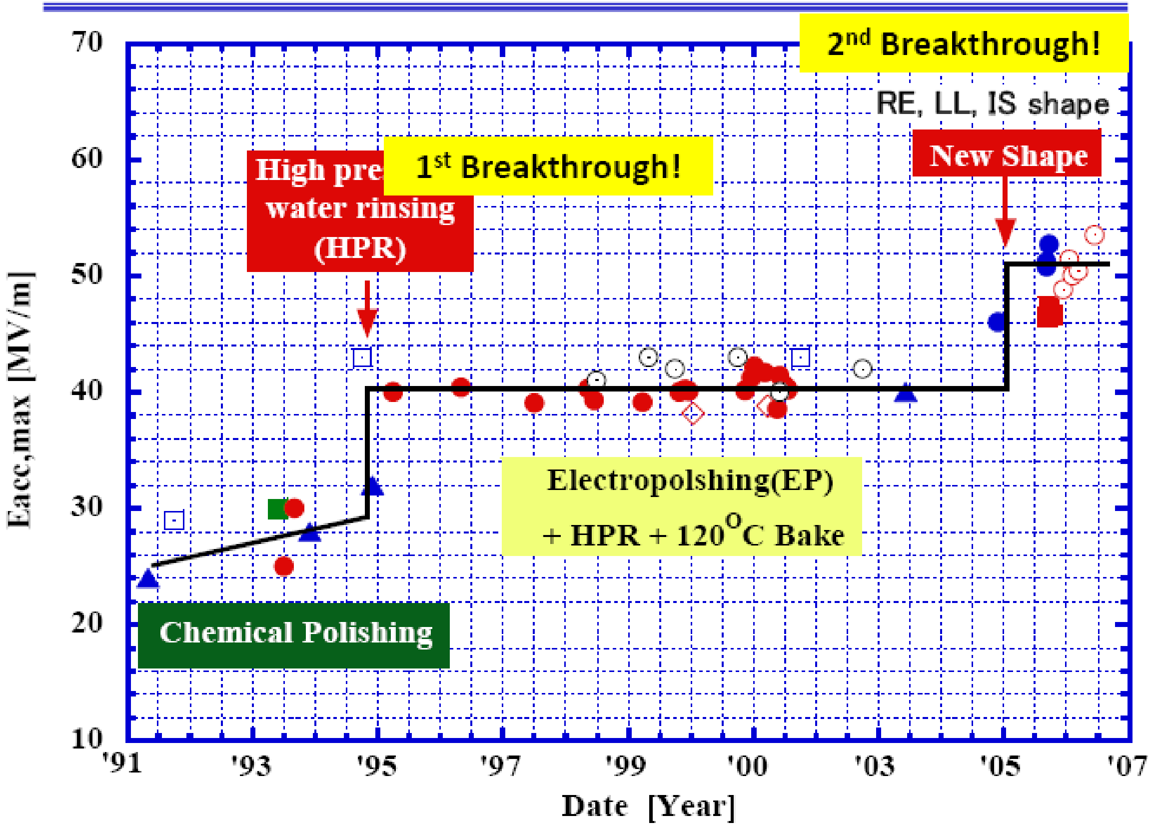
R&D on elliptical cavities for high beta linac sections with general impact



DESY, TESLA - cavity



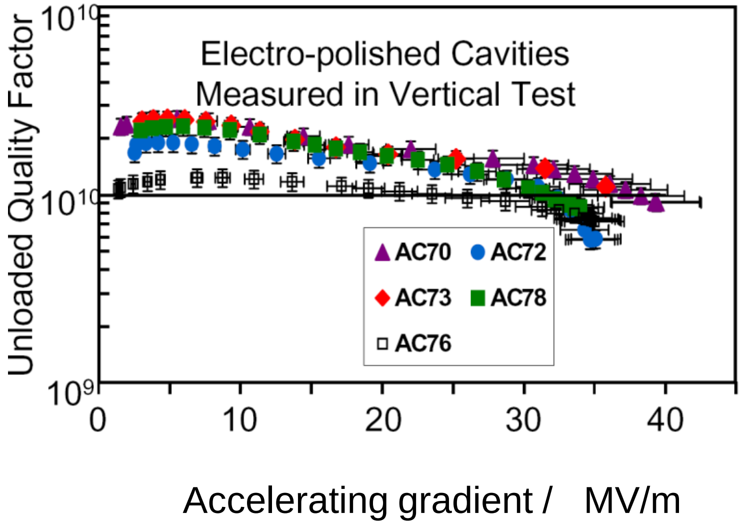
K.Saito IPAC2012 Talk

Tesla – type cavities

50 MV/m
at 1.3 GHz, 2K!
Critical magn. field would allow up to 57 MV/m!

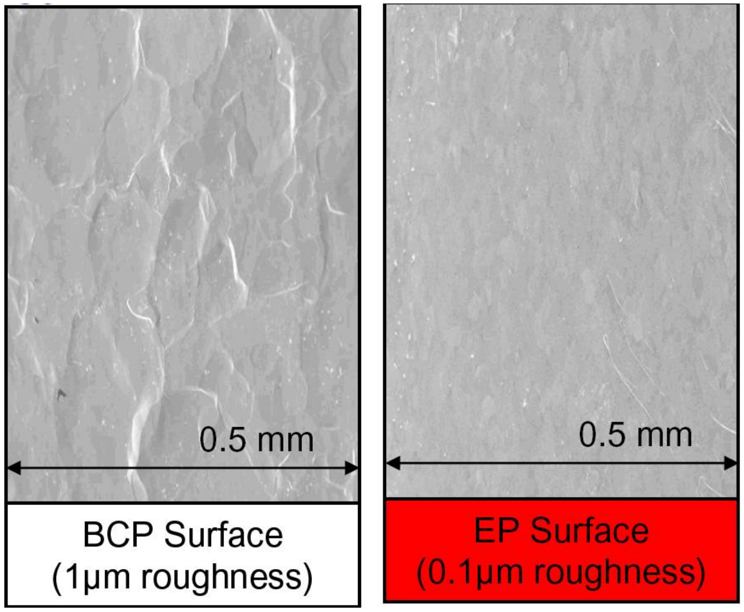
Higher acceleration fields

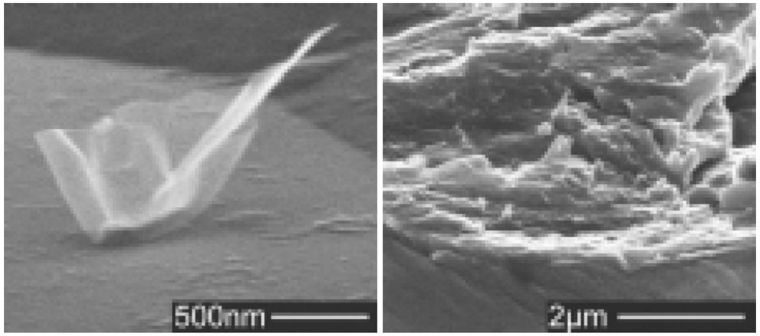
Aiming for high acceleration field, surface preparation



Achieved Q/E curves for Tesla cavities at DESY, D.Reschke et al.

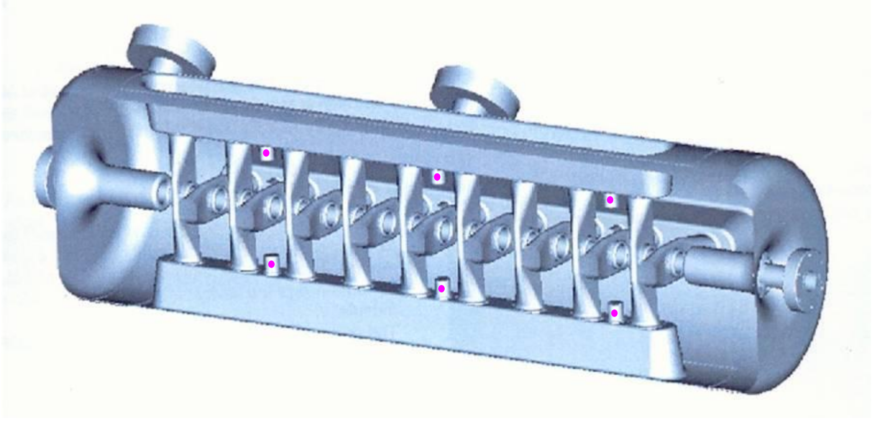
At ~ 50 MV/m the magnetic field limit of Nb (~ 200 mT) is reached for the TESLA type cavity.

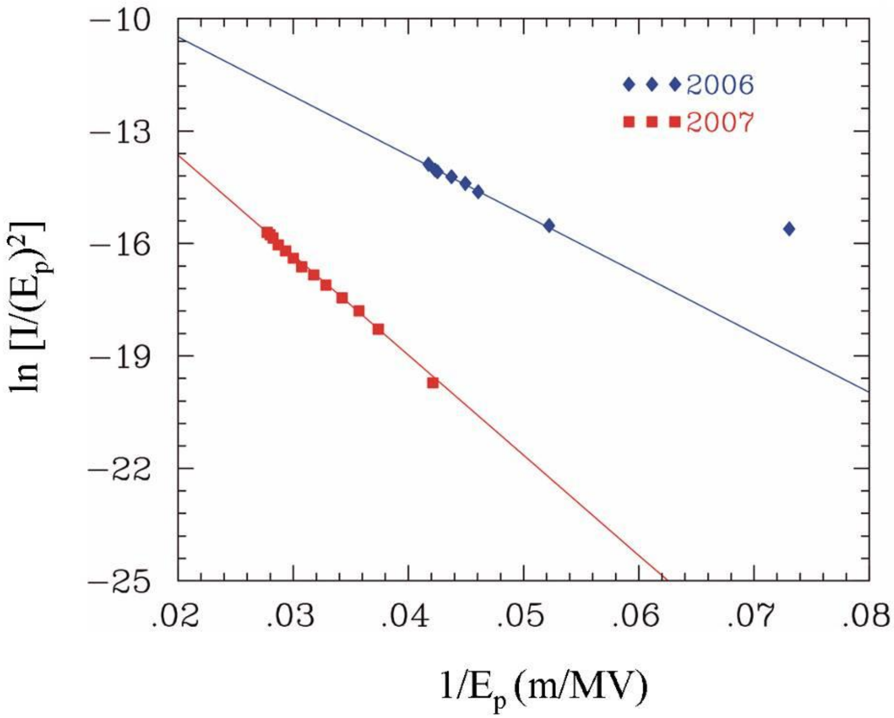




Higher acceleration fields

S.C. low energy structure development at IAP Frankfurt, 4 K



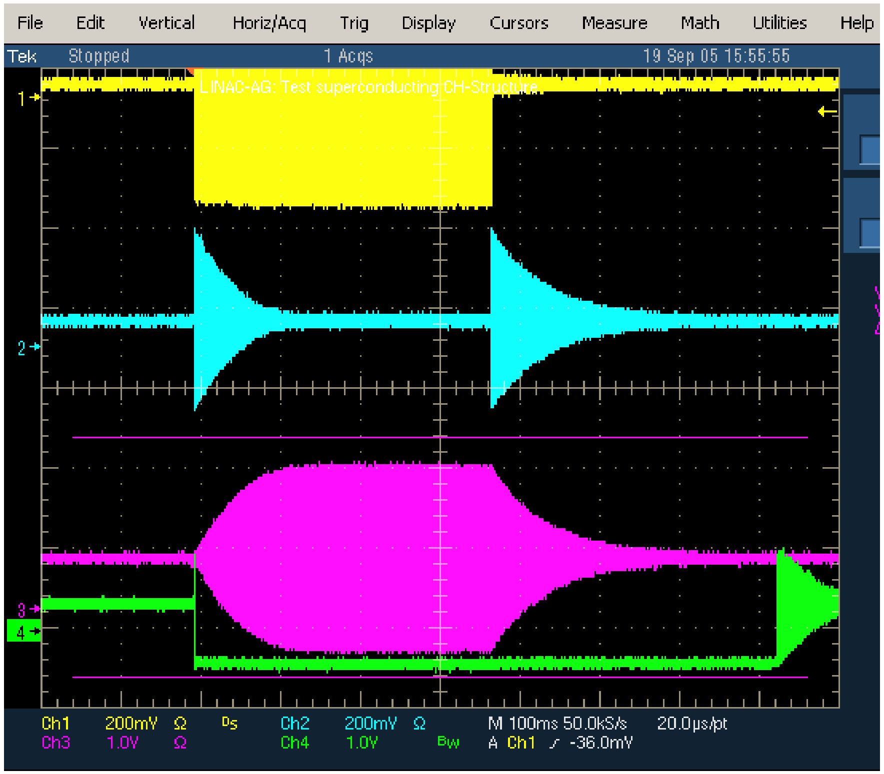


325 MHz, 4 K, 10 % speed of light

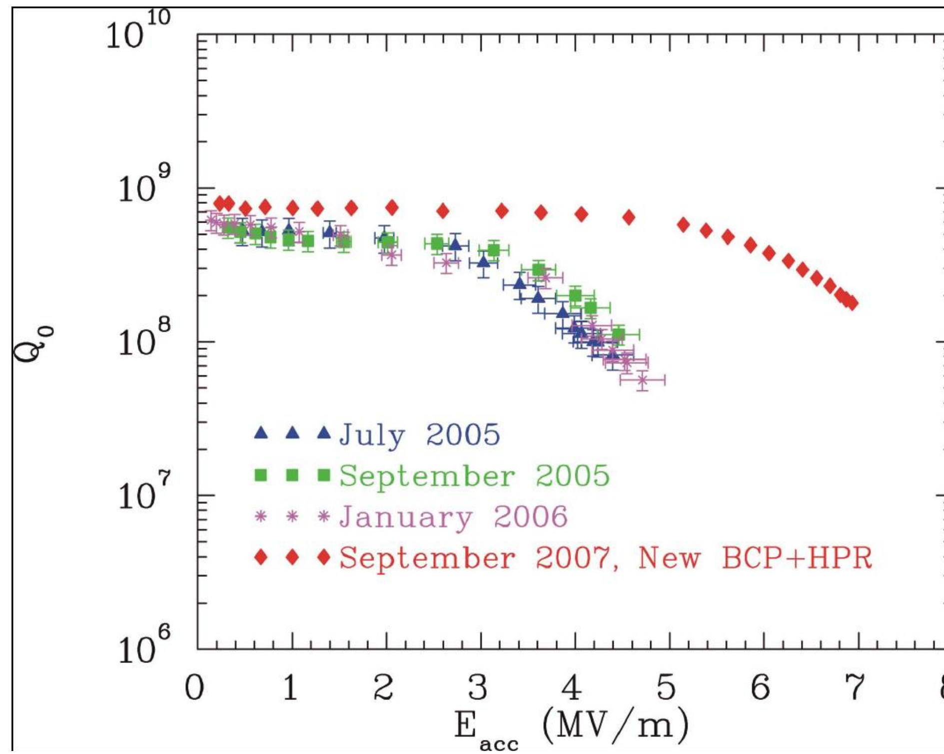
$\beta_{2006} = 350$
$\beta_{2007} = 200$

Higher acceleration fields

Superconducting CH Cavity Development at IAP



Incoupled (yellow), reflected (blue) and outcoupled (pink) rf signal; 100 ms per div.



Quality factor against effective field gradient.

State of the art results, SC cavities

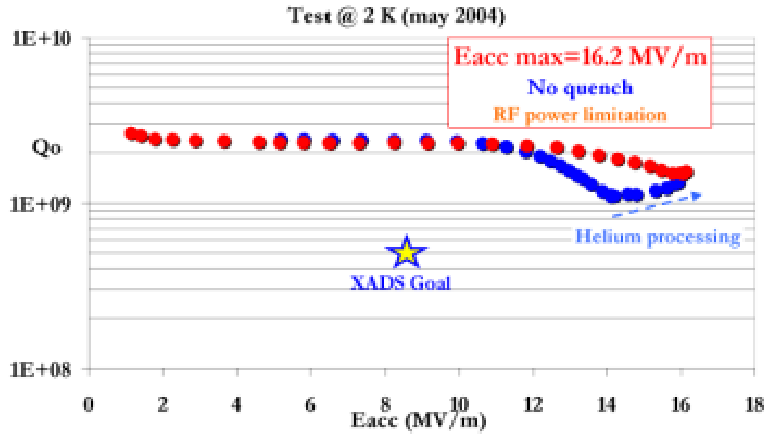
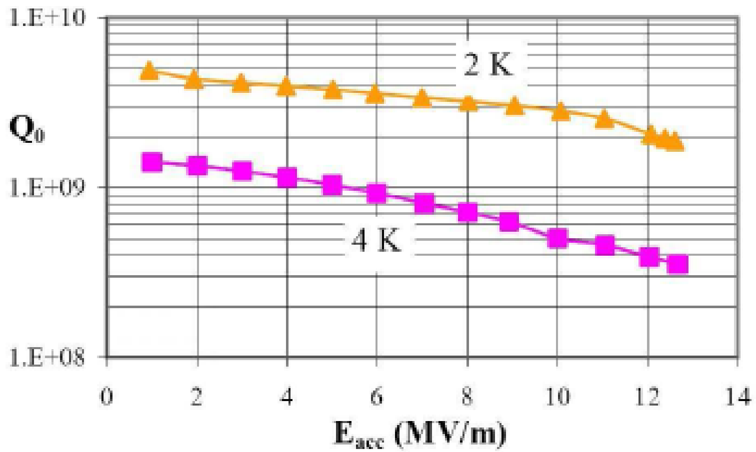


Figure 7: Q-curve of a 352 MHz, β=0.35 single-spoke cavity [15].

Single Spoke cavity during fabrication

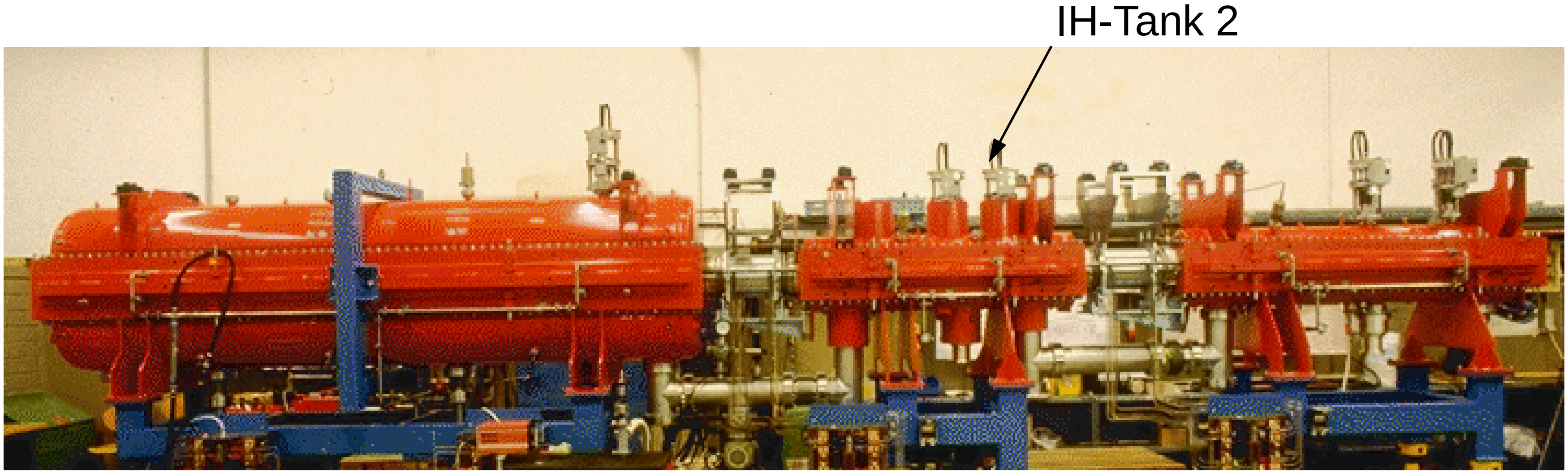


Q-curve test results for a 350 MHz β=0.175 single-spoke cavity developed at LANL.

Lit. on Spoke cavities:
M. Kelly, Superconducting Spoke Cavities, Proc. Of the LINAC12 Conf., Tsukuba, p. 337

State of the art results, RT cavities

CERN Linac 3, design: 33 MV voltage gain along 8 m beam line
Effective voltage gain of 4.1 MV/m

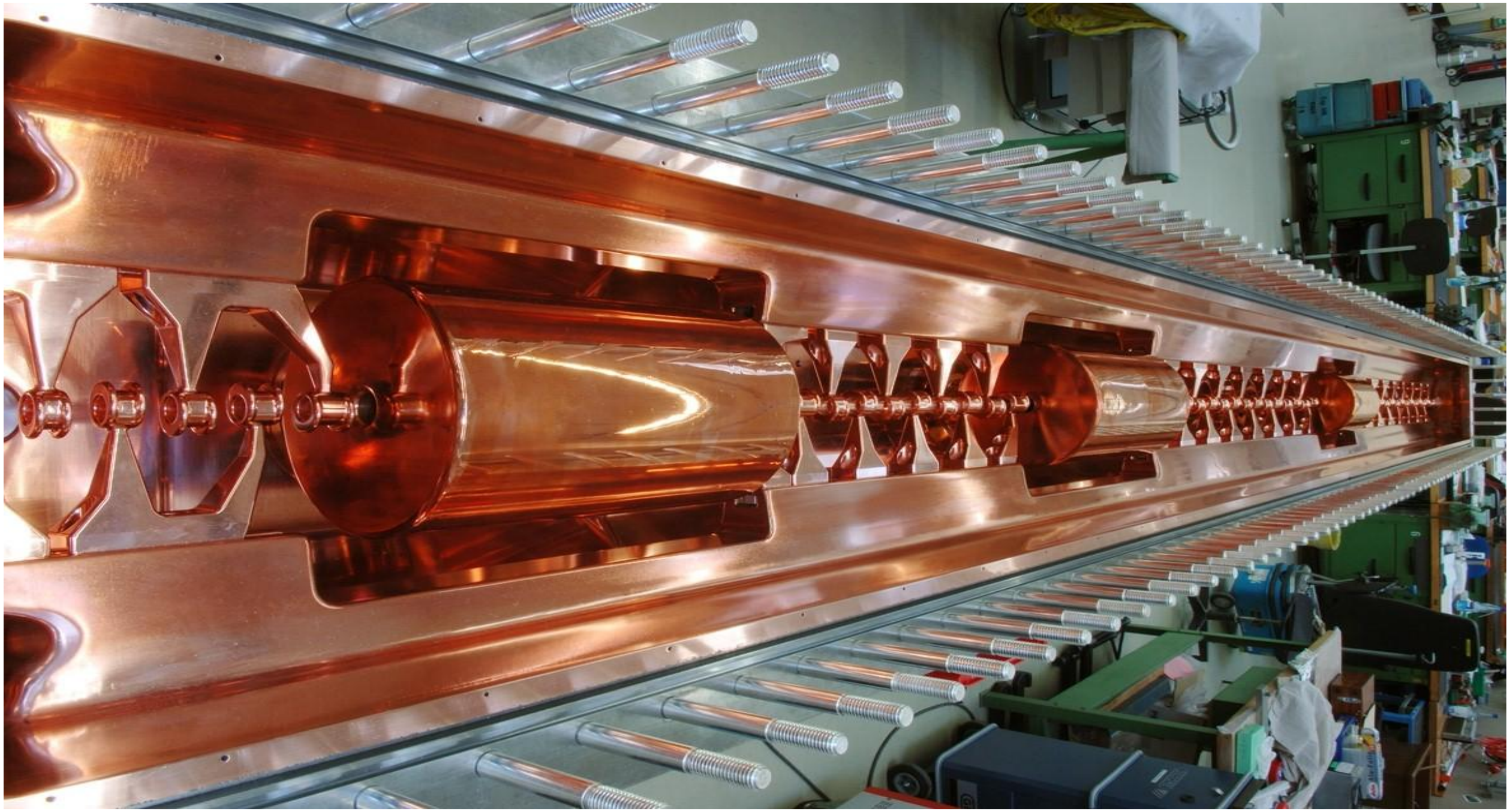


101 / 202 MHz combination, in operation since 1994.

State of the art results, RT cavities

HIT Heidelberg, 7 AMeV C4+ - Therapy injector, 20 MV on 3.8 m

5.25 MV/m effective voltage gain!

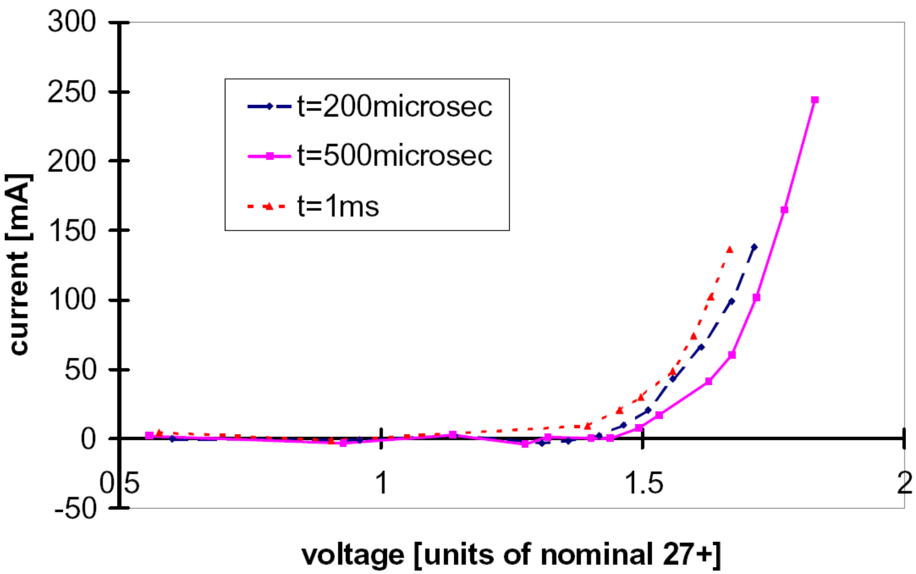


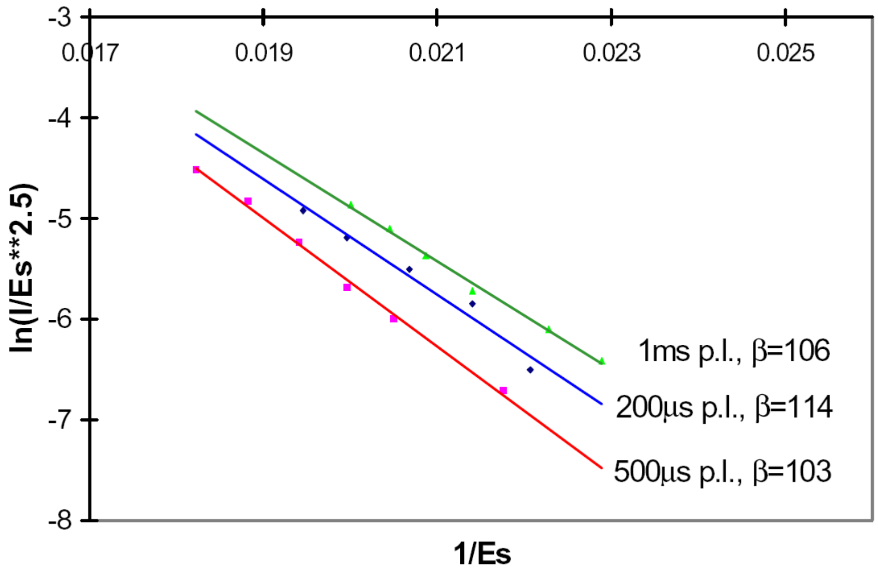
217 MHz, in operation at HIT Heidelberg, CNAO Pavia,
under construction at Marburg, Shanghei, Medaustron at Wiener Neustadt

State of the art results, RT

High power tests on CERN Linac 3, IH-Tank 2

Surface fields up to 54 MV/m, eff. acceleration up to 10.7 MV/m



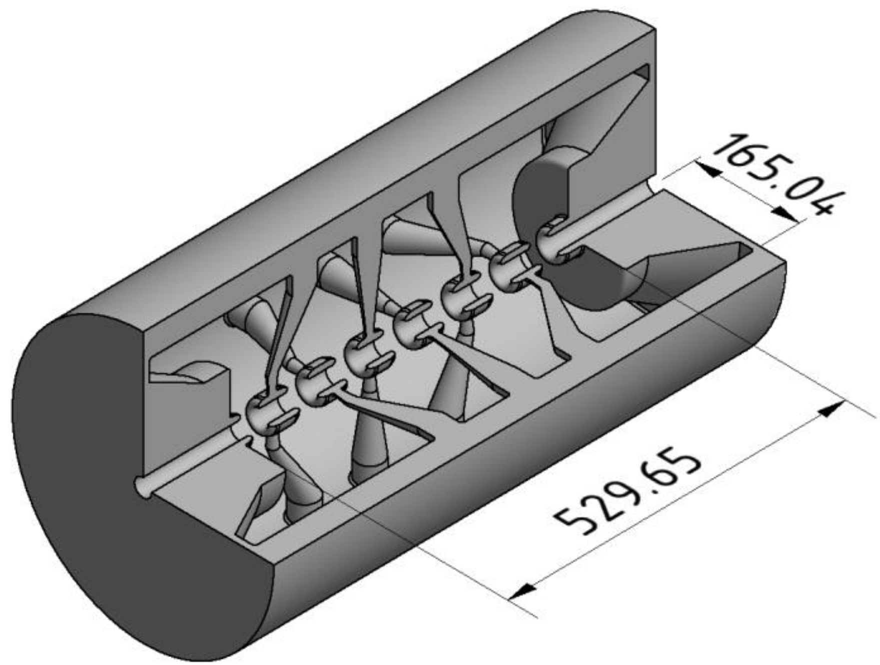


Q_0

RT cavity R&D

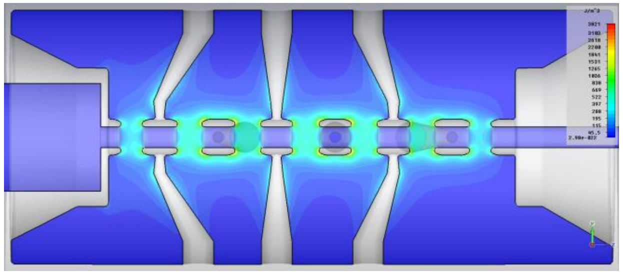
New BMBF -project at IAP Frankfurt:
Layout , construction, surface treatment and rf power tests on a 325 MHz, r.t. CH - cavity

Table 1: The main CH – cavity parameters for the high – field gradient prototype.	
Number of Gaps	7
Frequency (MHz)	325.2
Voltage Gain (MV)	6
Eff. Accel. Length (mm)	529.65
Eff. Accel. Field (MV/m)	11.2
Power Loss (MW)	1.58
Q_0 – value	13500
Effective Shunt impedance (MΩ/m)	57.3
Beam Aperture (mm)	27

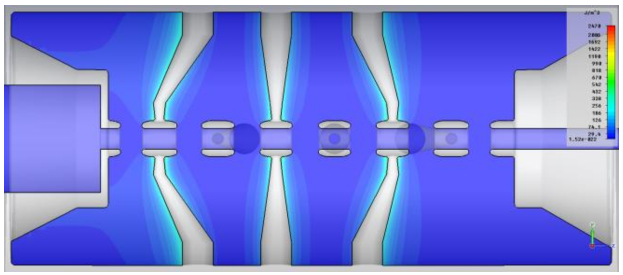


Q_0

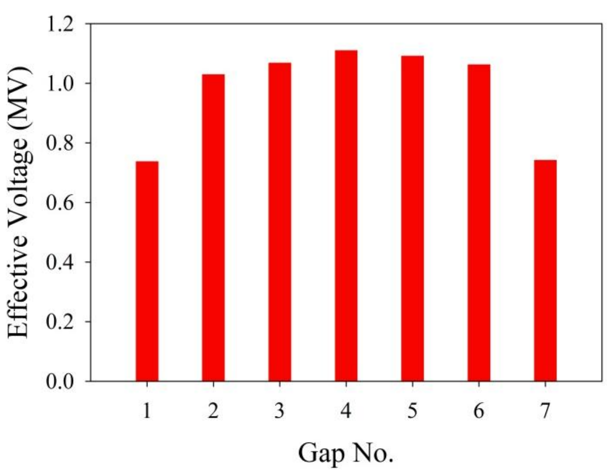
RT cavity R&D



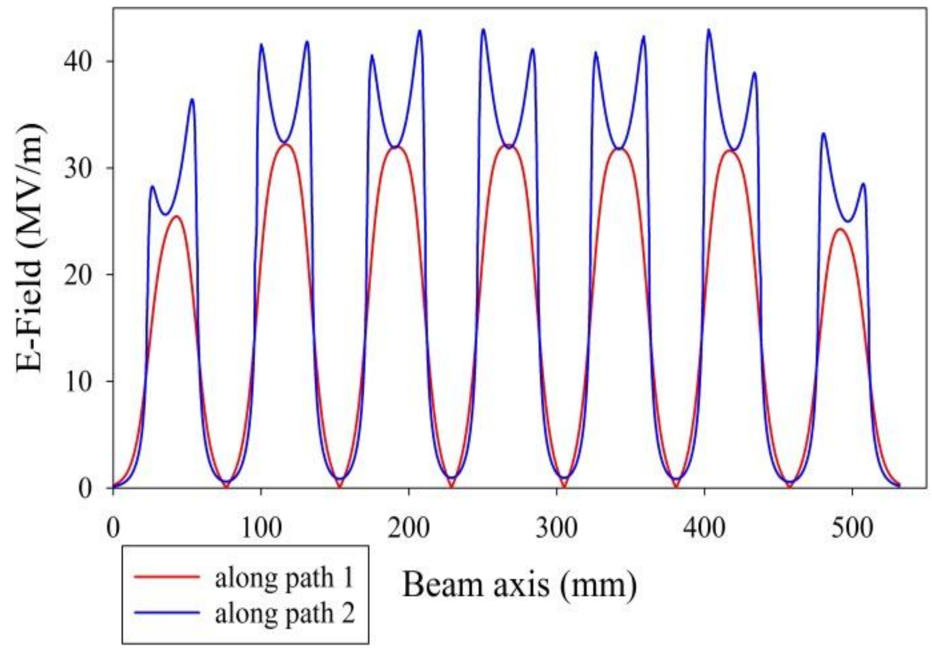
$|\vec{E}|$ -field distribution



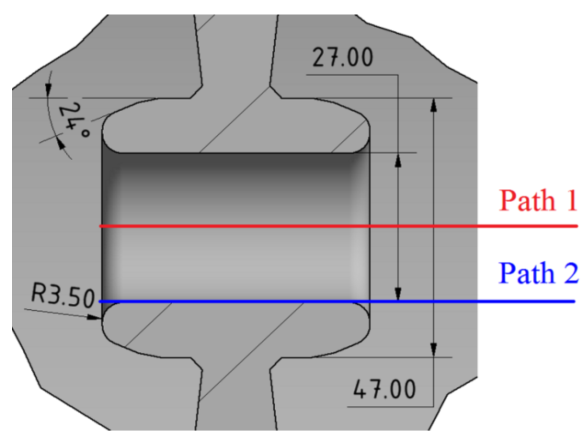
$|\vec{B}|$ -field distribution

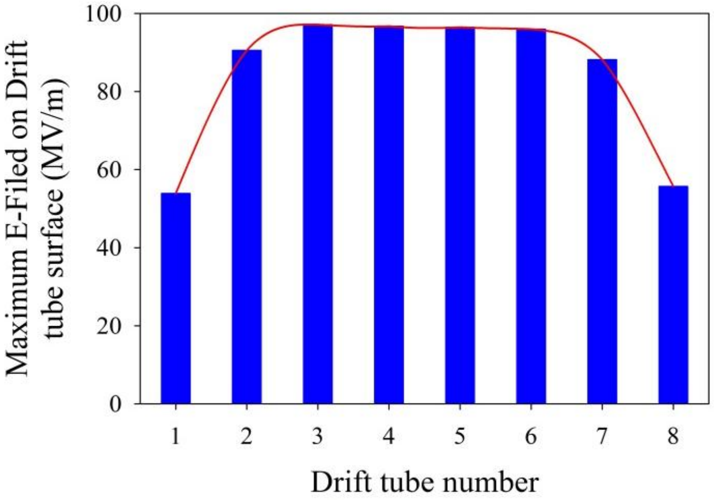


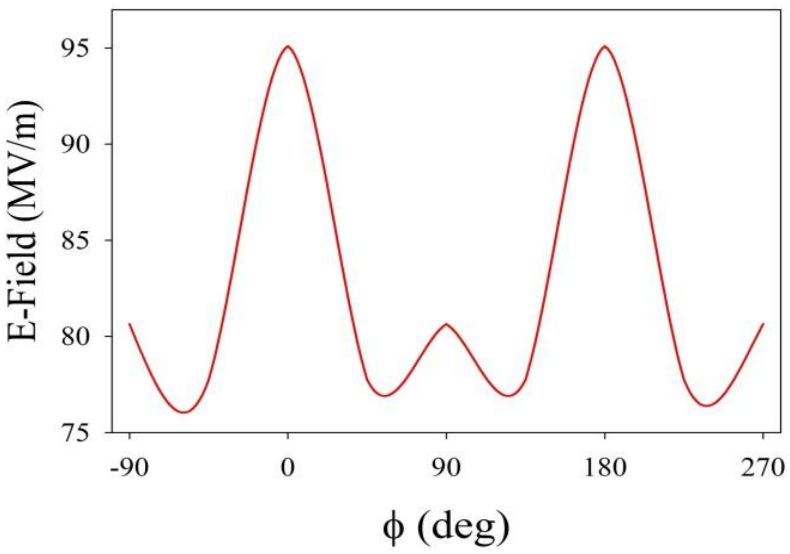
Eff. gap voltage distribution



$|\vec{E}|$ -field distribution along z-axis and in parallel at the aperture radius of 13.5 mm

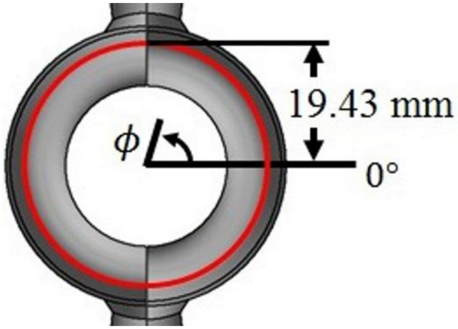




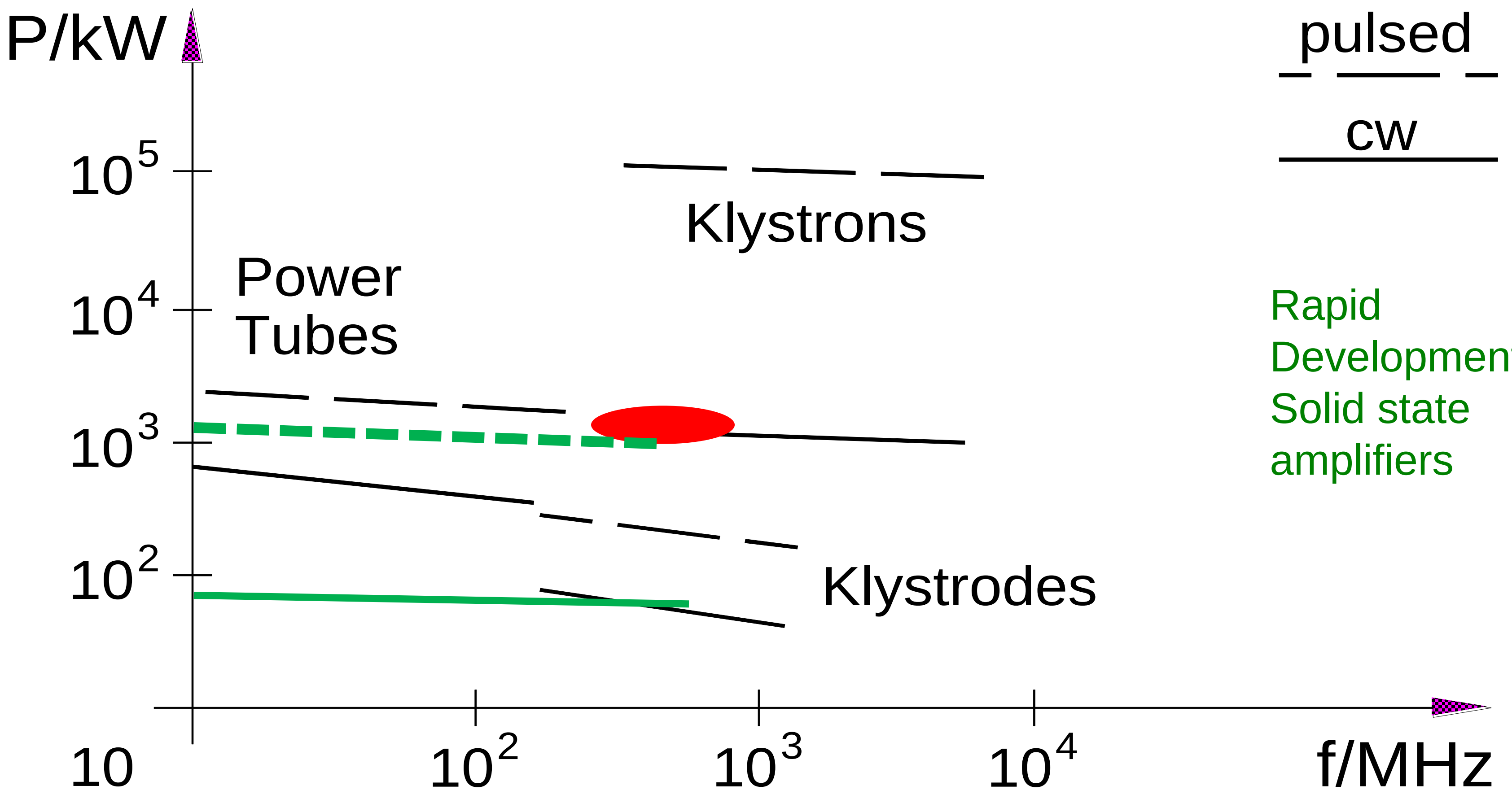


E_{max} – spots at r = 19.43 mm for each drift tube and half – drift tube

Azimuthal field strength distribution for drift tube no. 3 (evidence for a modest quadrupole field component)



Improved rf amplifier technology



Rapid Development: Solid state amplifiers

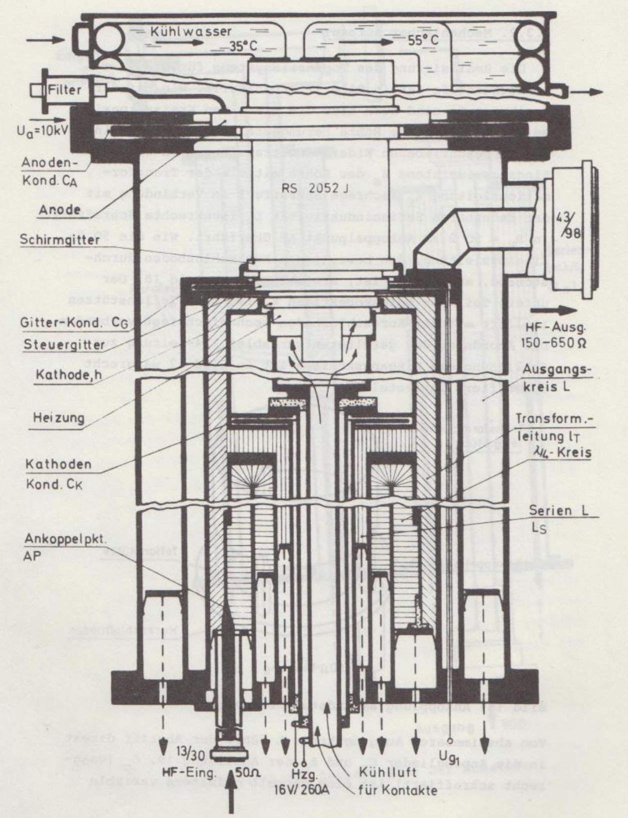
Improved rf amplifier technology

Tube driven cavity amplifiers
10 MHz to 300 MHz

Problems:

- Shrinking market because of revolution in communication technology
- power tube logistics, delivery guarantees, quality control

This is affecting heavy ion facilities mainly.



Improved rf amplifier technology

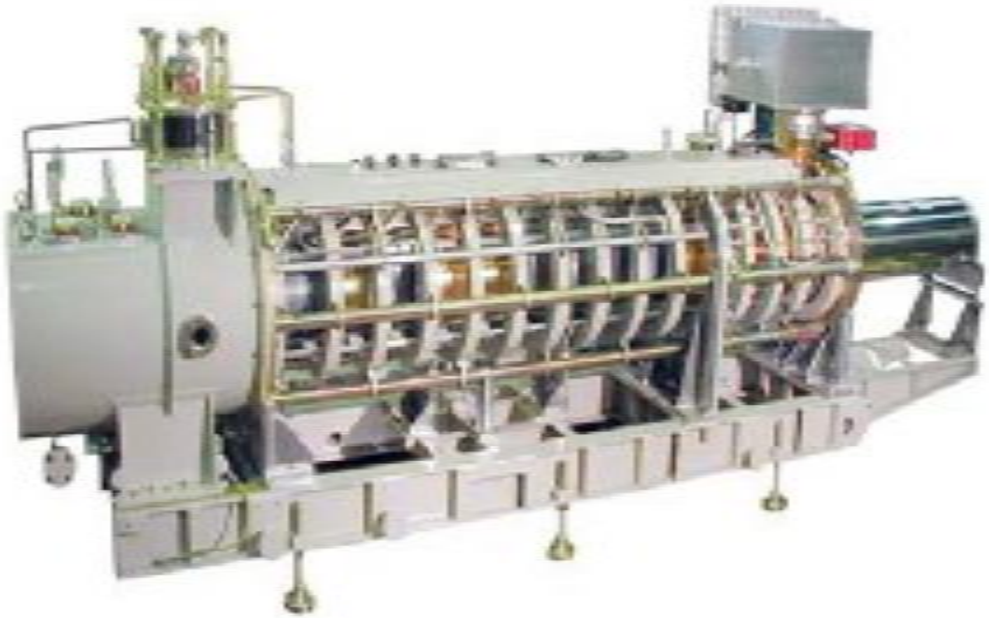
Power klystron technology pushed by electron machines first (SLAC)
Meanwhile frequencies down to 325 MHz are well established.

Advantage: - Long lifetime (about 40000 hours typically)

Disadvantage: - Becomes quite bulky at lower frequencies

- expensive modulator developments for every beam pulse structure (100 kV …. few 100 kV)

Toshiba, 3 MW, 325 MHz Klystron,
100 kV modulator to be developed specifically.



Improved rf amplifier technology

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Solid state amplifiers

•MOSFET – transistors develop rapidly:
Output power per transistor doubled every year

•Besides Si based technology (Freescale…) in future
also SiC – technology may contribute (Infineon…)

•Very attractive prizes in case of pulsed operation:
(up to some 10 kW per transistor feasible, V up to 1 kV)

•Forced liquid cooling

•Service during operation at reduced power possible

•Falling investment costs per 1kW of installed power

Example in Si – technology: 30 kW cw, 87 – 108 MHz,
Three 19 inch racks like shown in the photo will do the job.
Rf to plug power efficiency about 55 %;Mass about 1800 kg.

(Photo Digital Broadcast DB, Padova, Italy)

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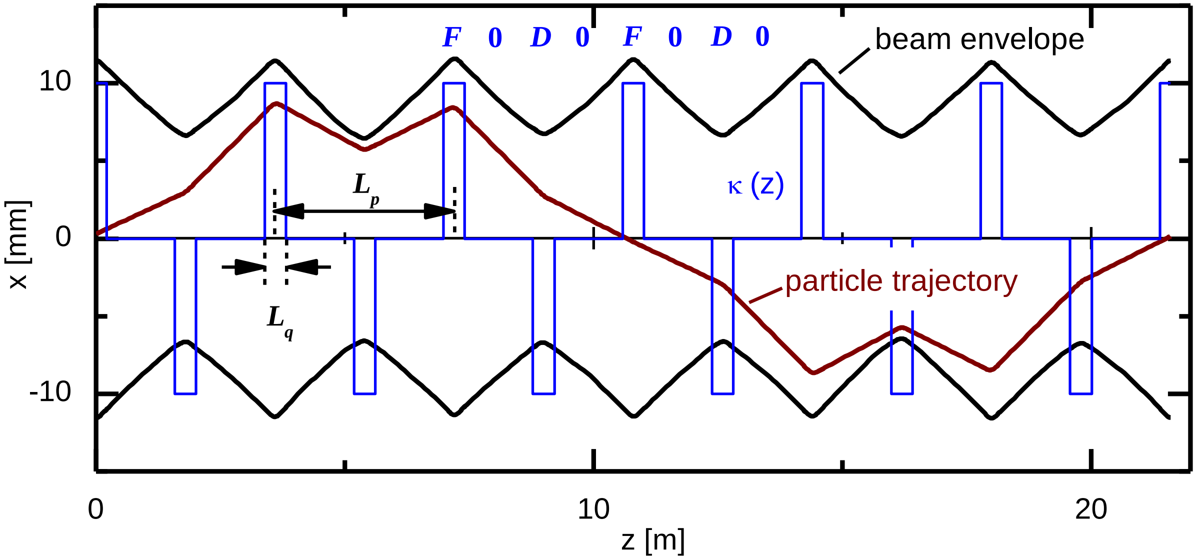
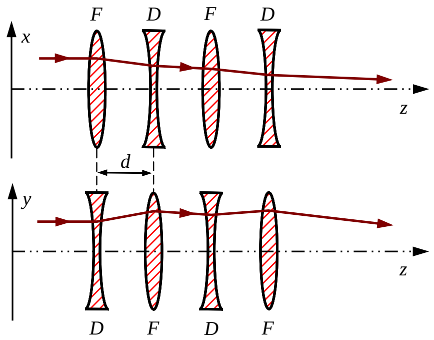
Linac focusing elements:

- Quadrupole singlet, doublet and triplet channels

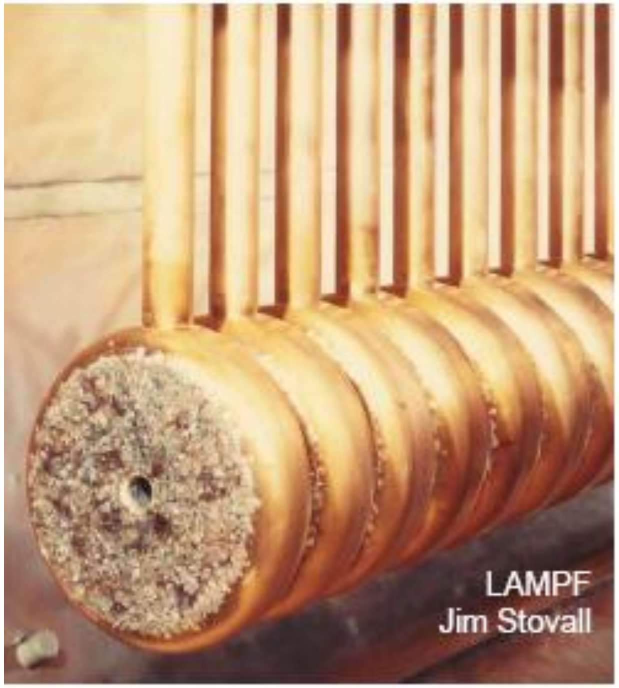


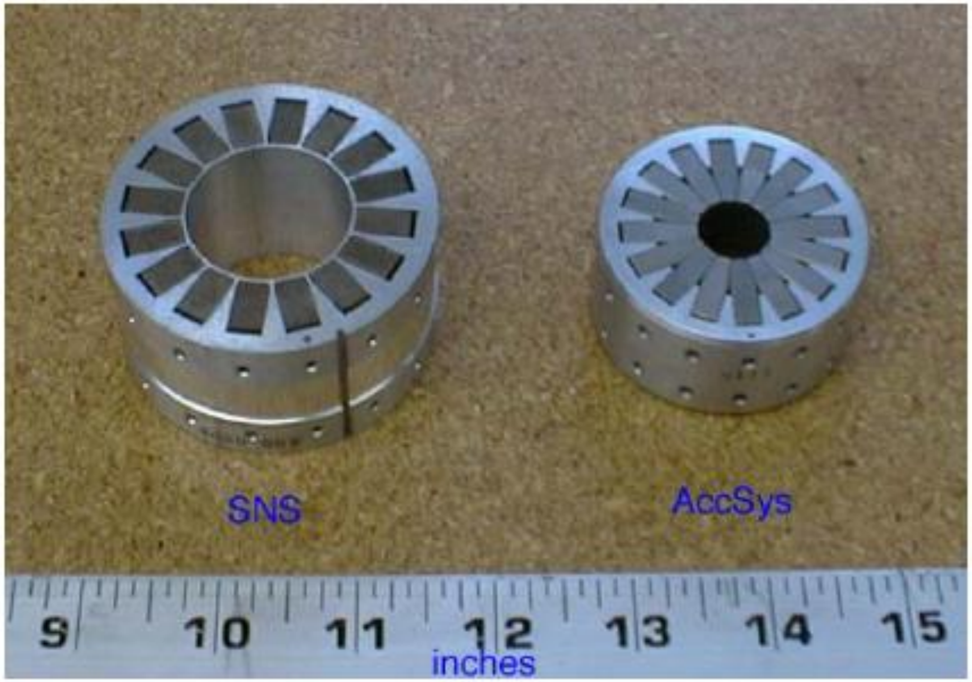


FODO – channel, 30 deg phase advance

Efficient transverse focusing

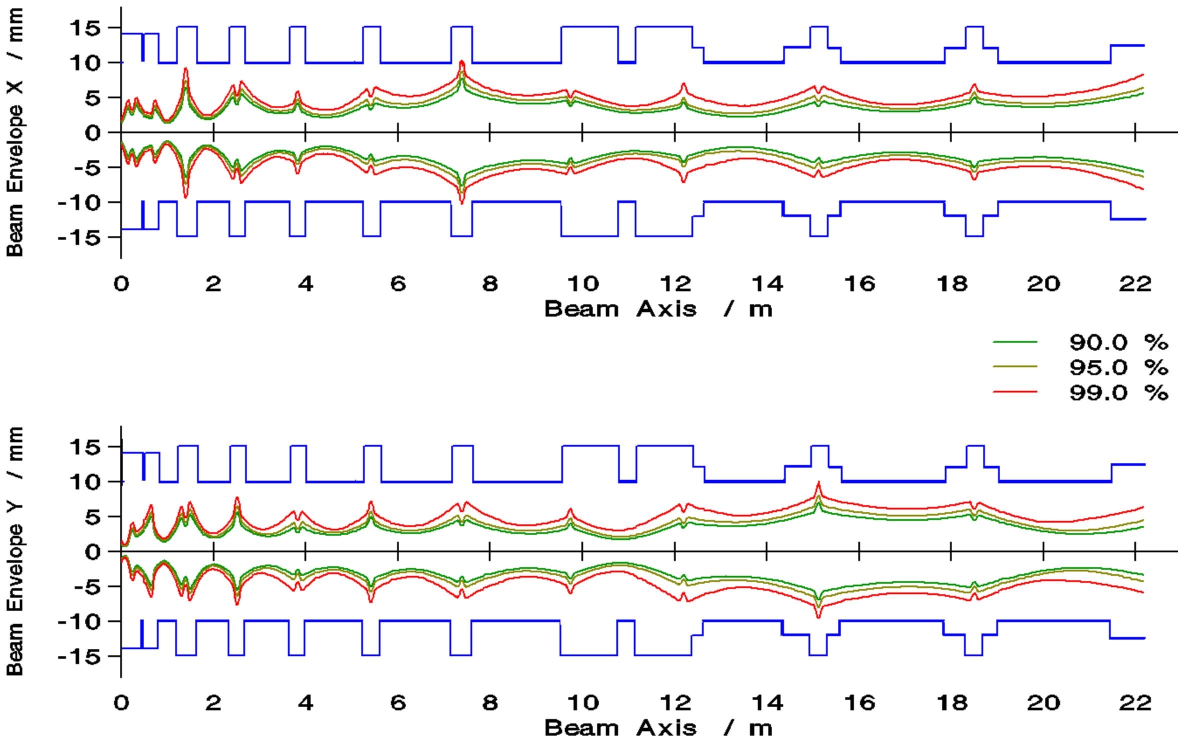
Especially at low beam energies DTL's with integrated electromagnetic quadrupoles suffer from multipacting between tubes with large outer diameter.
A new trend is to use more compact permanent magnetic quadrupoles.
At Los Alamos, IH-DTL development with PMQ's is underway (S.S. Kurennoy et al.) Phys.Rev.STAB2012





Efficient transverse focusing

Quadrupole triplet focusing between r.t. CH cavities at FAIR – proton linac: 3 -70 MeV, 70 mA, 22 m. Beam dynamics G. Clemente et al. IPAC10.

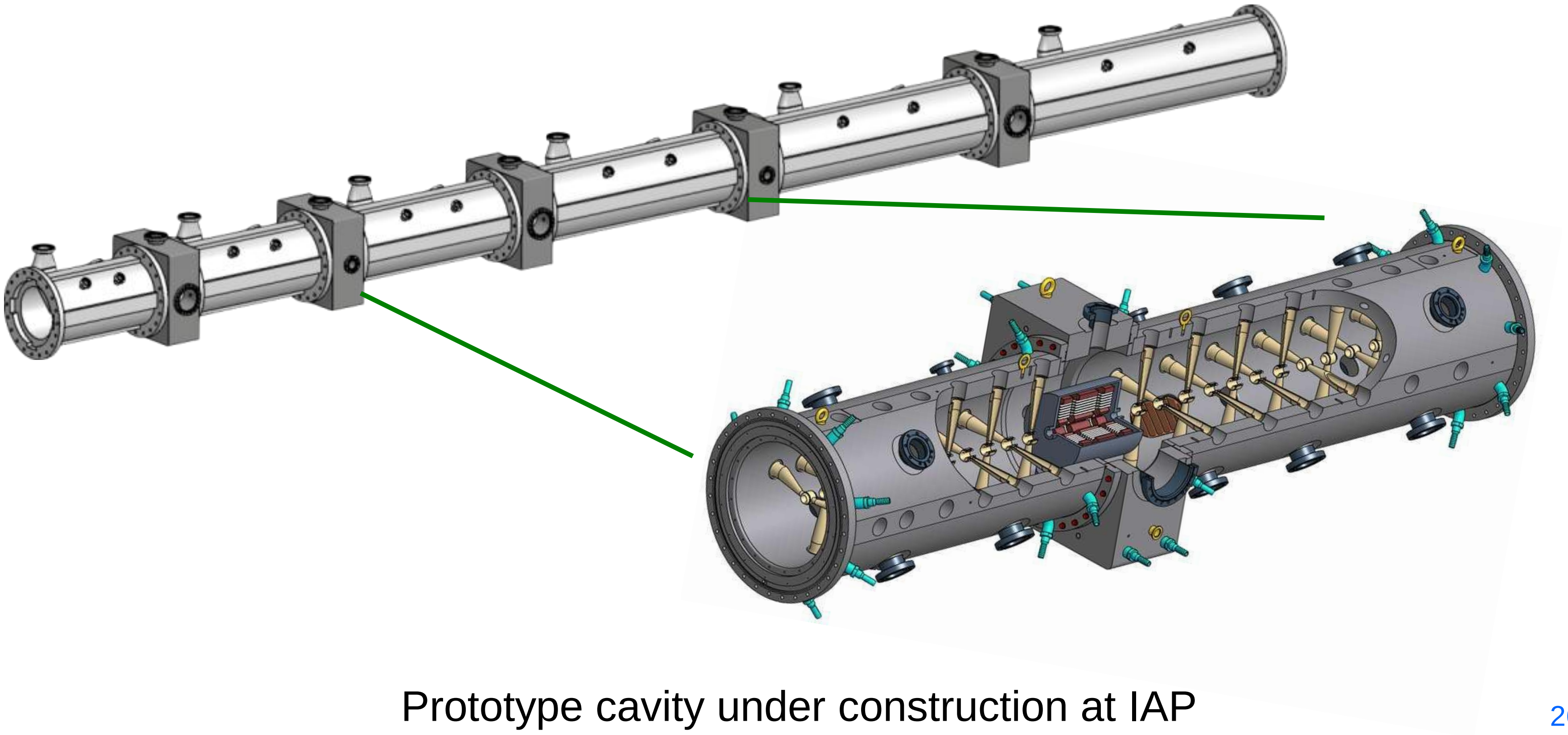


Efficient transverse focusing

Mechanical concept, 3–35 MeV, 70 mA section:

A 9 m long tank consists of 3 coupled CH – cavities. Every second triplet is housed in a drift tube for rf coupling to CH drift tube sections.

Doublets and triplets can be aligned mechanically at the workshop and form a complete transverse focusing unit. Not true for singlet channels!



Prototype cavity under construction at IAP

Efficient transverse focusing

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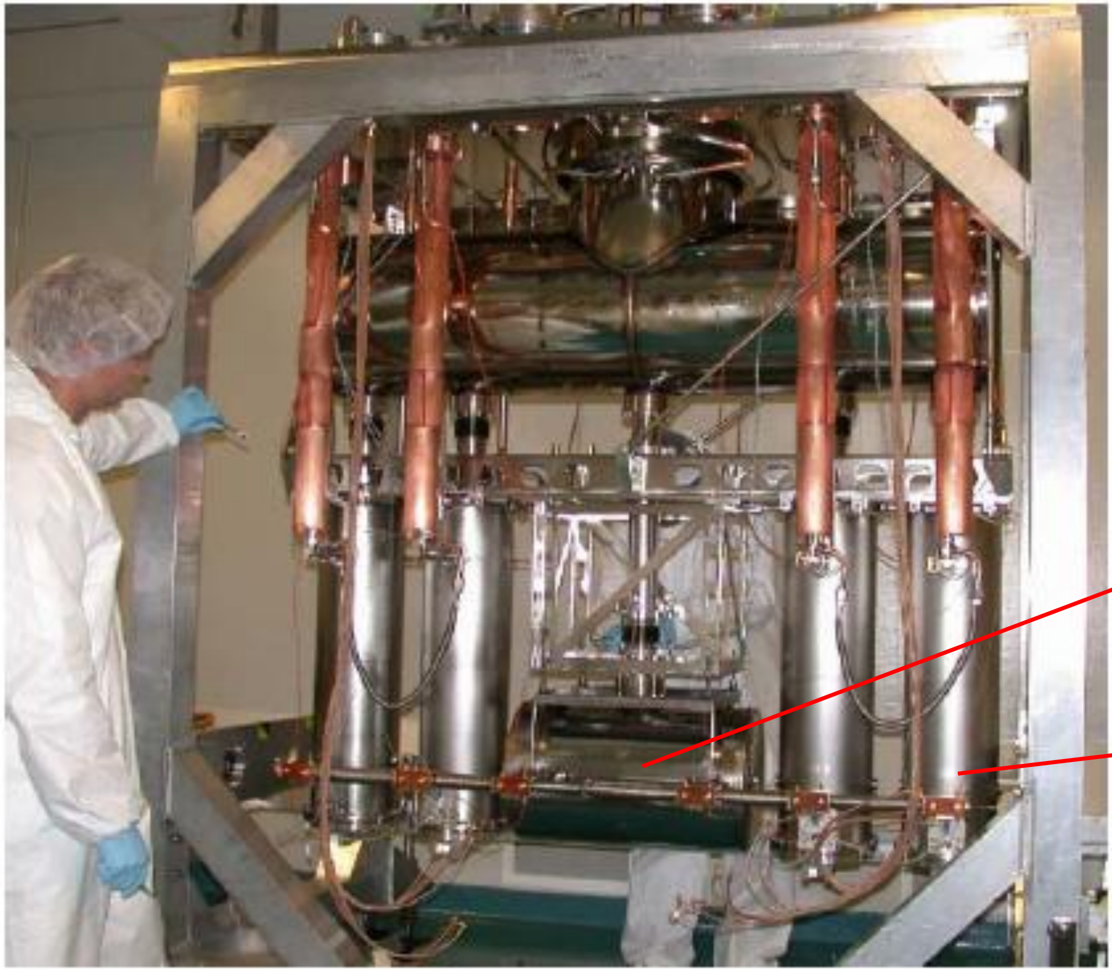
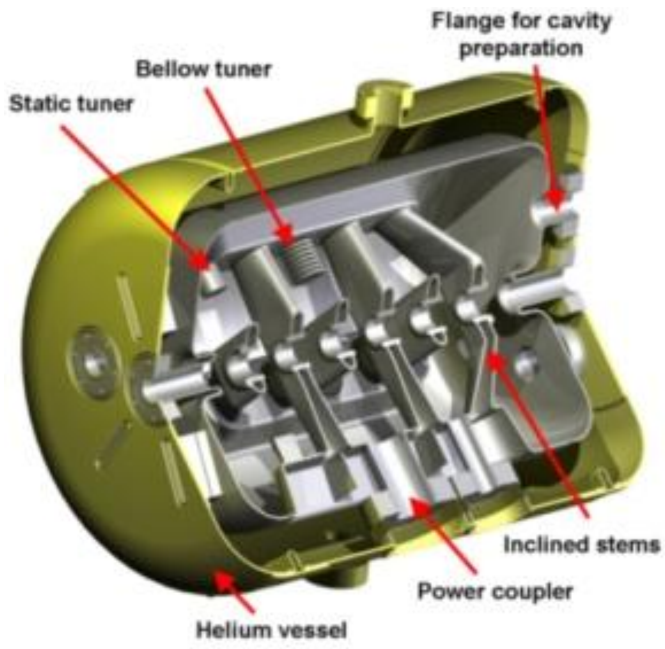


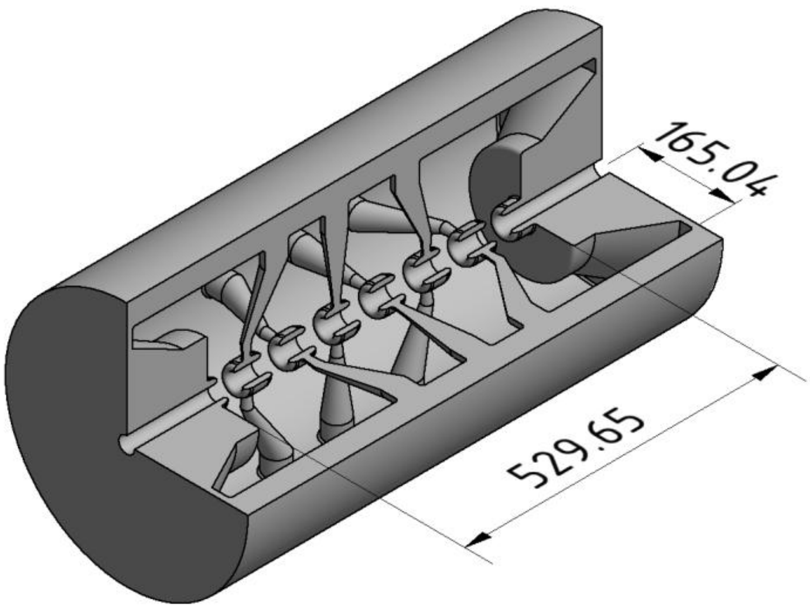
Solenoid

Quarter wave resonator

S.C. solenoids integrated in cryostat with cavities. Coaxial shielding end coils provide steep field edges to protect the cavities.
TRIUMF ISAC2, Vancouver, Canada
R. Laxdal et al. LINAC 2006

S.C. CH – cavity, 325 MHz against pulsed R.T. CH – cavity, 325 MHz; $\beta \approx 0.15$.



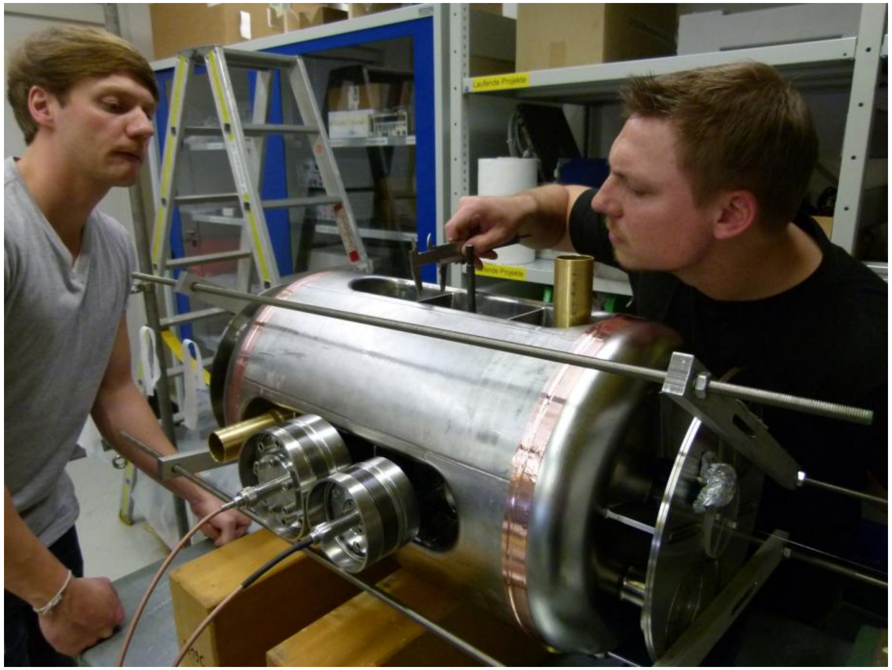


S.C. cavity ready for cold tests

R.T. cavity under design

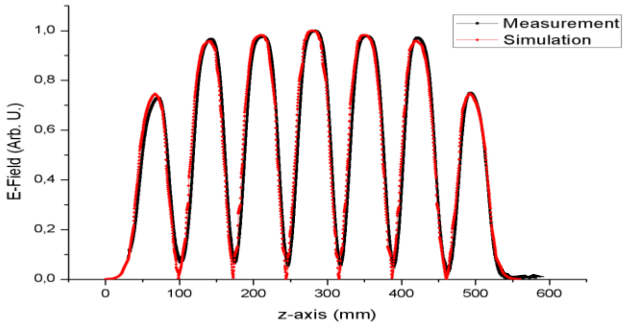
Cavity development at IAP Frankfurt and in cooperation with GSI Darmstadt

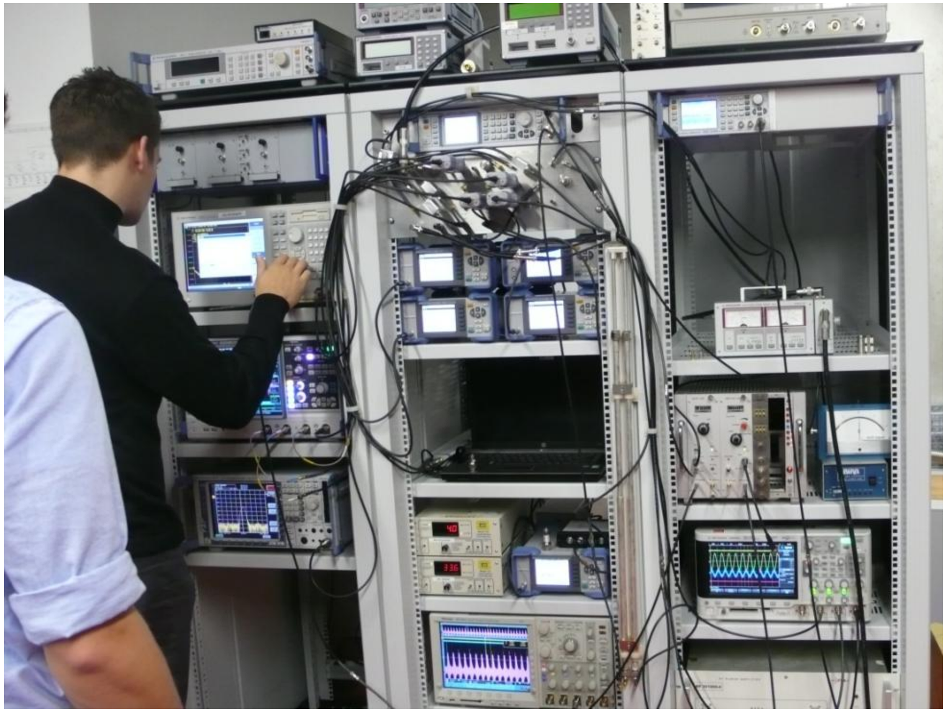
SC versus RT technology, duty factor



Fabrication of the new 325 MHz CH – cavity, $\beta = 0.15$, at Company RI, Bergisch-Gladbach, and two doctorands during an RF tuning procedure

SC versus RT technology, duty factor





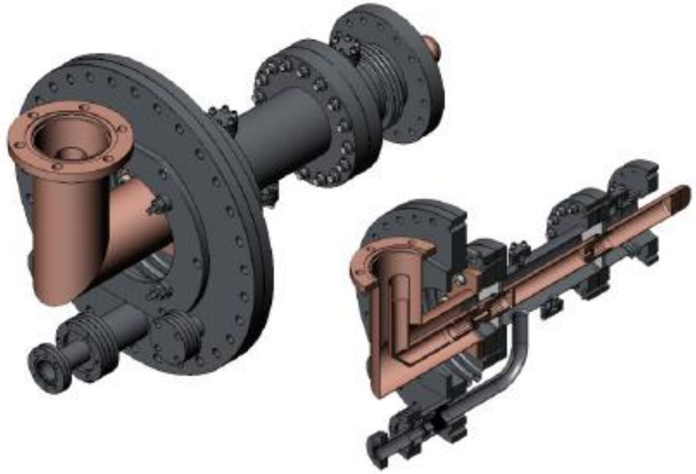
First measurements on the new 325 MHz CH – cavity at IAP Frankfurt in 12/2012.
Aims:

- Exact Unilac frequency
- High acceleration gradient
- Test with Unilac beam at 11.5 AMeV

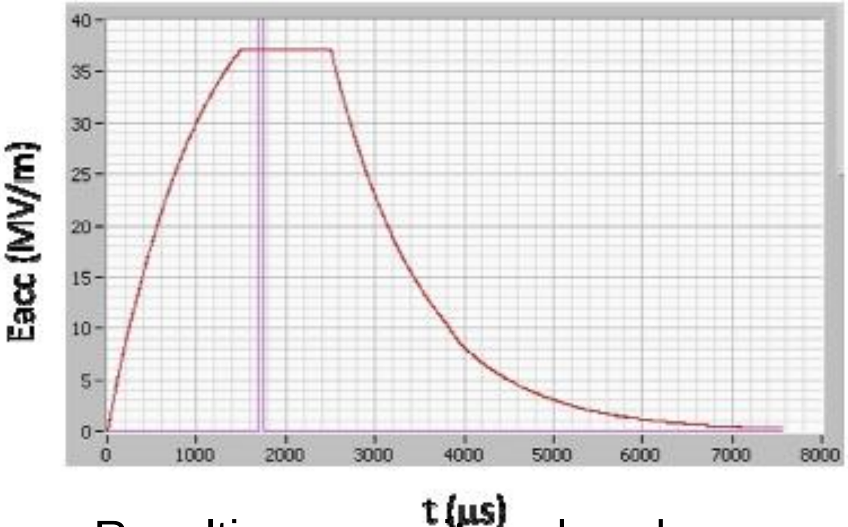
SC versus RT technology, duty factor

An important detail for sc technology: The input power coupler.

The coupling factor determines the cavity quality factor.
At high beam current the Q- value can approach rt cavity values.
At low beam current the coupler allows to adjust reliable operating conditions.



Power coupler development at FNL



Resulting sc cavity pulse shape

Lit.: R. Madrak et al.,FERMILAB-Conf-11-063-APC

SC versus RT technology, duty factor

It is expected that r.t. approaches will benefit from new rf power generation schemes:

Solid state amplifier revolution!

SC versus RT technology, duty factor

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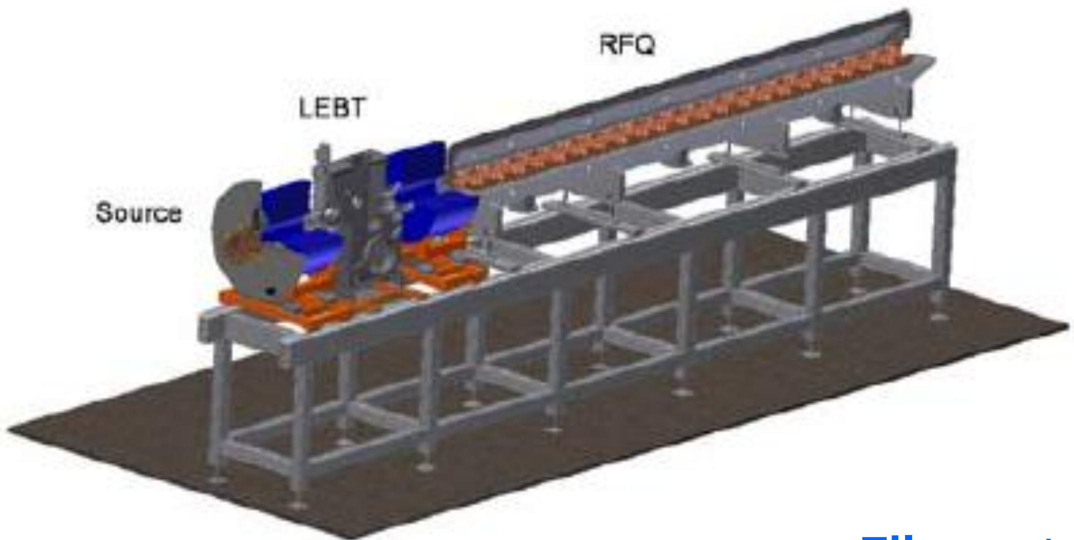
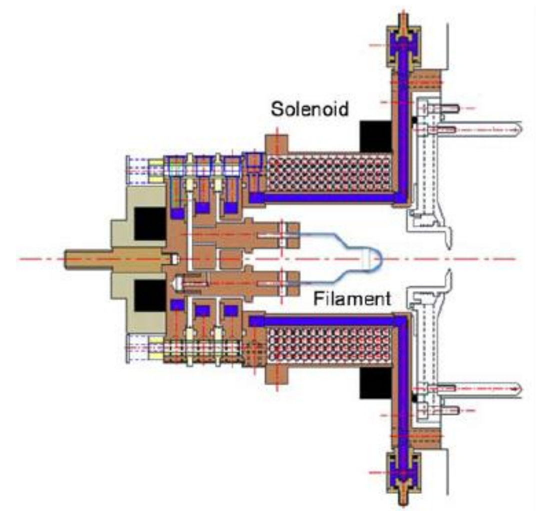
Design Study for a rt pulsed 500 mA p- injector





- Filament driven ion source
- LEBT with two solenoids
- 162.5 MHz 4Rod-RFQ
- Based on efficient solid state amplifiers

Table 1: Main parameters of the 500 mA front-end

Parameter	Value	Unit
Particles	protons	NA
Current	500	mA
Platform voltage	150	kV
Source	volume type	NA
LEBT	magnetic	NA
RFQ	4-Rod	NA
Frequency	162.5	MHz
Energy	2	MeV
Duty factor	5	%

A PULSED LINAC FRONT-END FOR ADS APPLICATIONS

U. Ratzinger, H. Podlech, A. Schempp, K. Volk, IAP, Goethe Universität Frankfurt am Main, Germany
O. Heid, T. Hughes, U. Hagen, SIEMENS AG
H. Höltermann, BEVATECH, Frankfurt

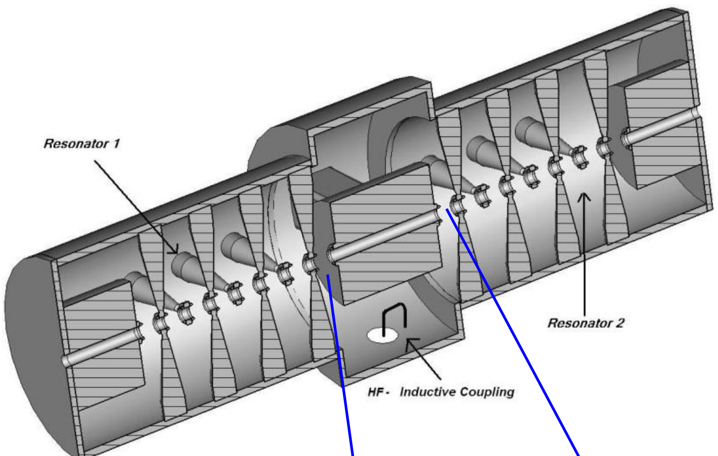
Proc. of LINAC 12, Tel Aviv

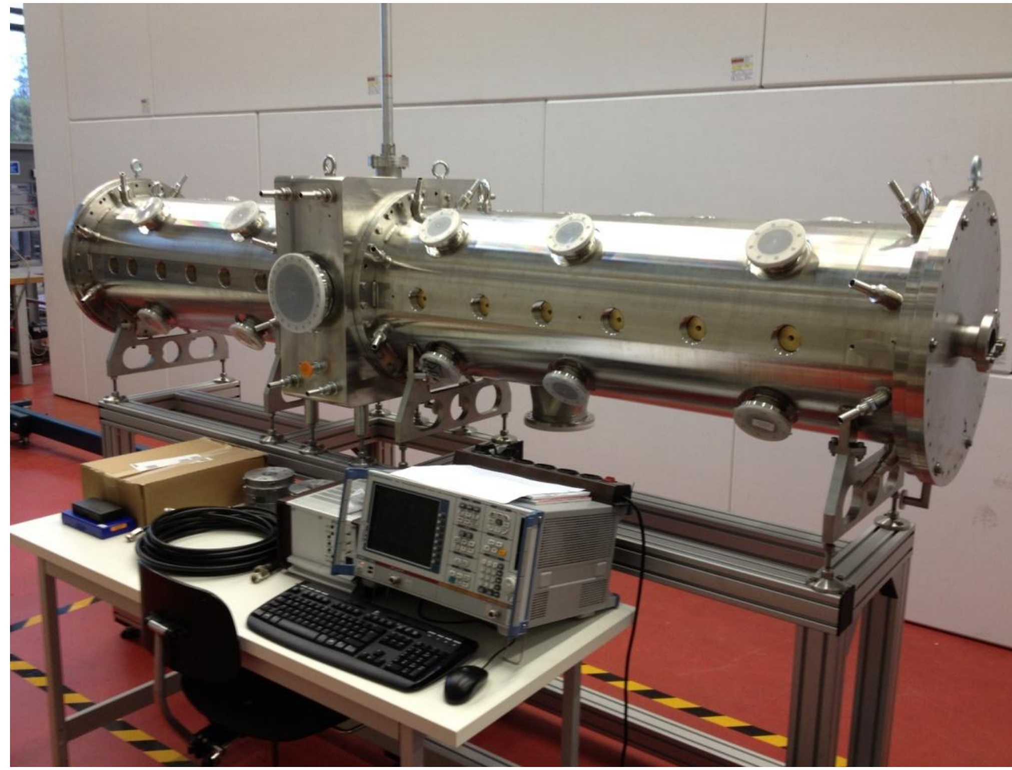
Motivation for a coupling of structures to form one resonator:

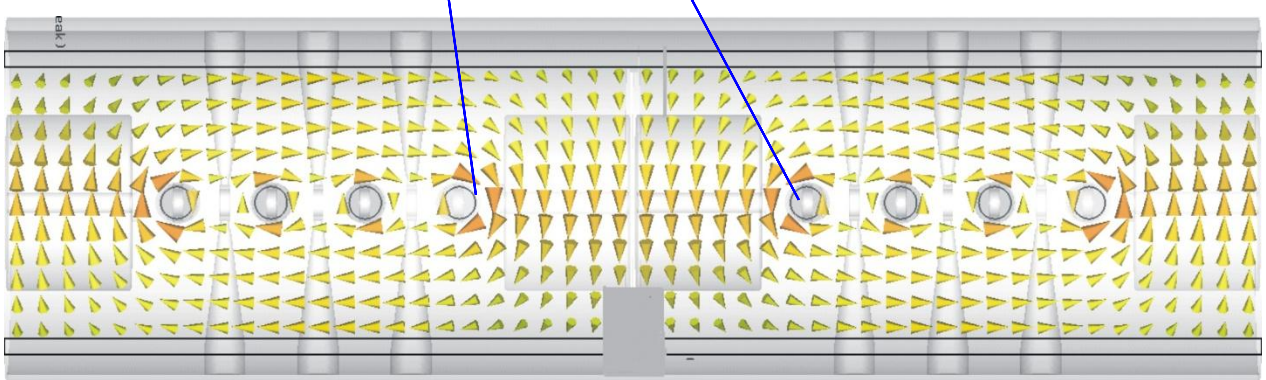
- Change of the structure at a certain beam velocity for an increased shunt impedance (at the end of an RFQ typically)
- Matching of the available rf amplifier power to the resonator
- Reduction of drift lengths between cavities.

Hybrid and coupled cavities

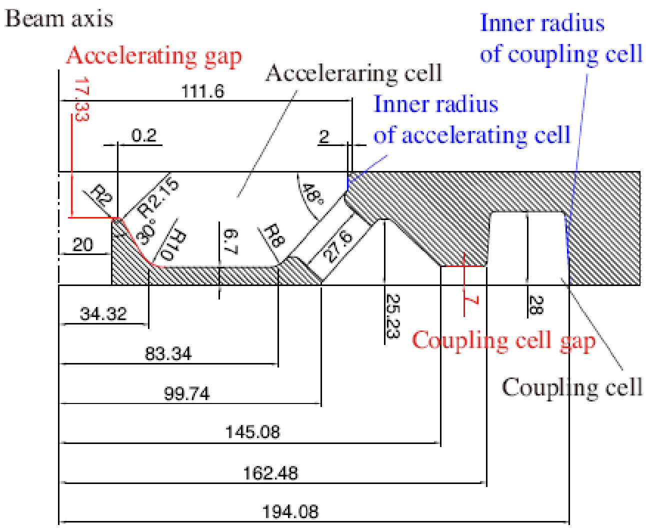
Two CH – sections are coupled to match the resonator rf power needs to the 3 MW klystron, 324 MHz from Toshiba

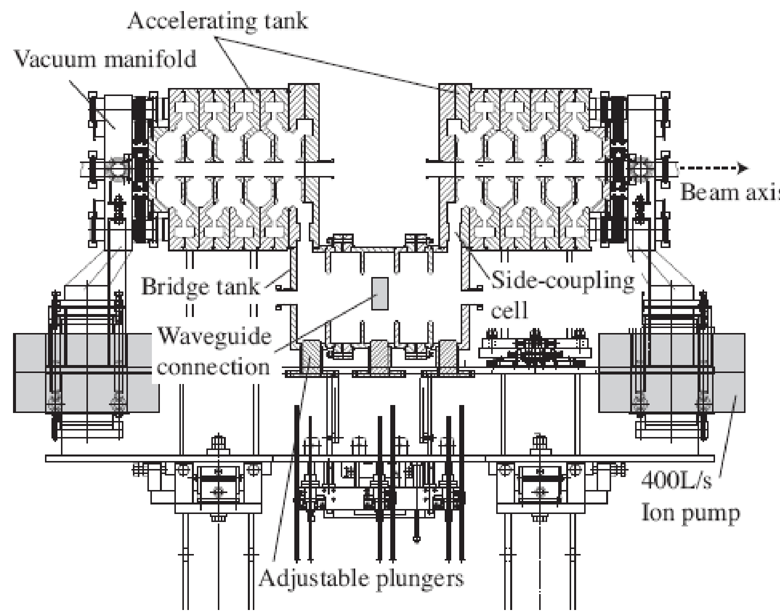


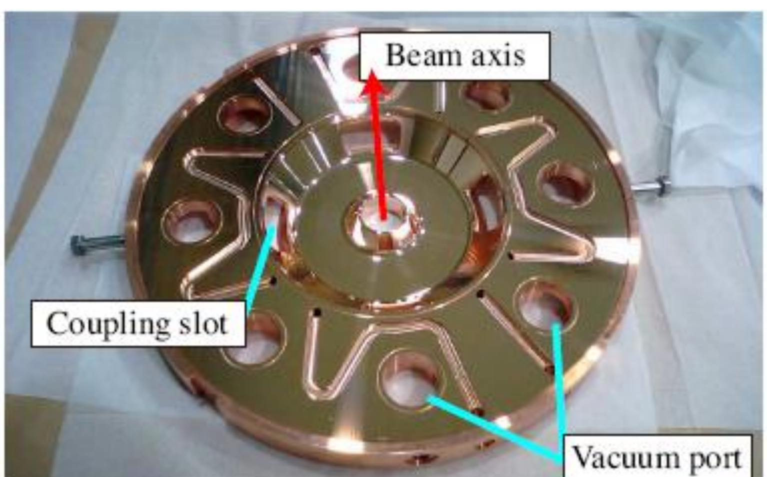




Hybrid and coupled cavities







Annular coupled structure ACS for JPARC from 190 MeV – 400 MeV
Under construction
Y. Yamazaki et al. LINAC 2006
Phys.Rev.STAB 2011

Cern Linac4 project to replace LINAC2 and lateron possibly to serve as a front end for a 2 GeV superconducting linac SPL.

CCDTL is under construction (M. Vretenar, F. Gerigk, LINAC12)

4-Ladder-RFQ and 4-Rod-RFQ development at 325 MHz

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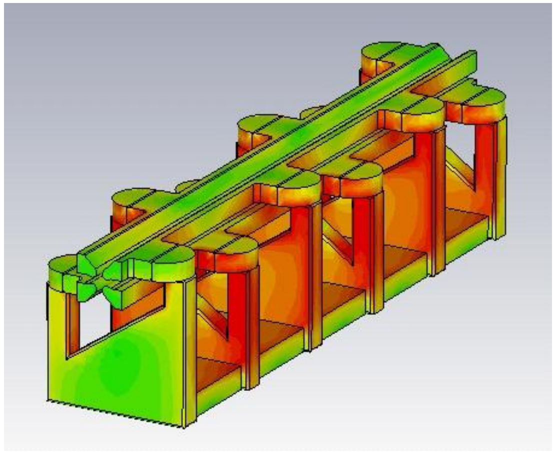


Table 1: **Main parameters of the Ladder - RFQ**

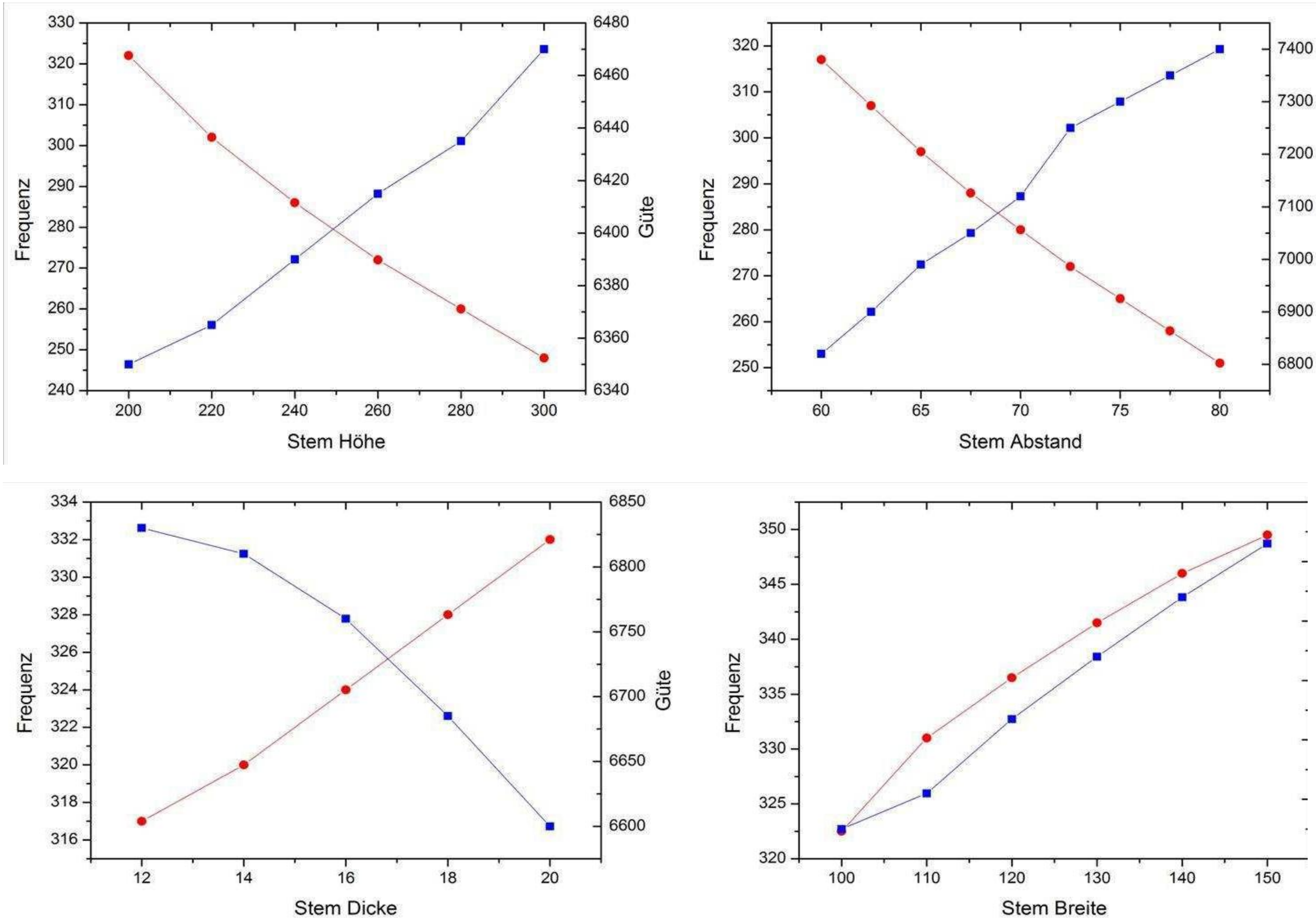
No. of RF Cells	52
Energiy Gain [MeV]	0.95 - 3.0
Q-Value (sim.)	8000
Frequency [MHz]	325.224
Stem Height [mm]	240
Stem Width [mm]	160
RF Cell Length [mm]	60

R. Brodhage, U. Ratzinger
A. Almomani, IPAC13, Shanghai

4-Rod-RFQ	**Type I**
Height beam axis [mm]	75
Stem width [mm]	100
RF cell length [mm]	50
Base plate height [mm]	12
Stem arm width [mm]	10
Frequency[MHz]	307.5
Dipole	1%- range
Frequency shift [MHz]	24,4
Q-value (sim.)	4100

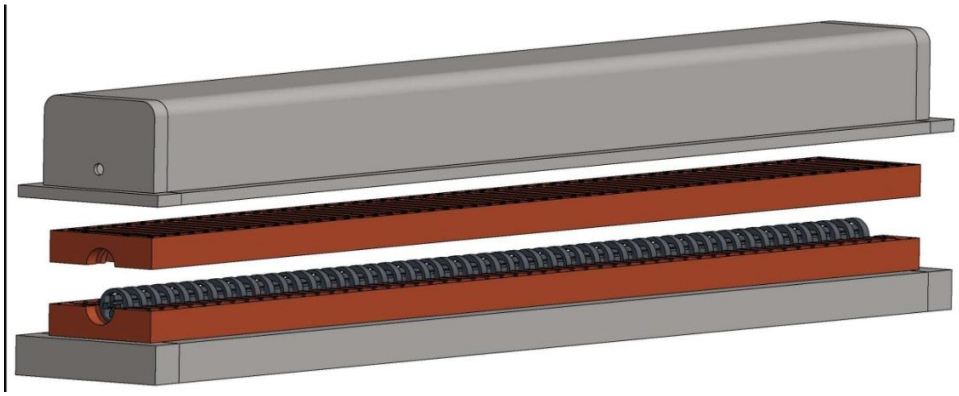
B. Koubek, H. Podlech, J.S. Schmidt,
IPAC13, Shanghai

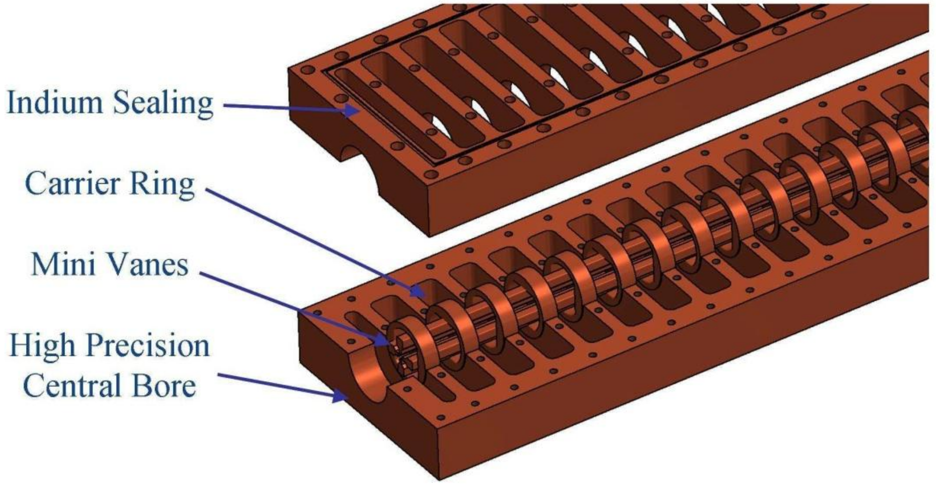
4-Ladder-RFQ

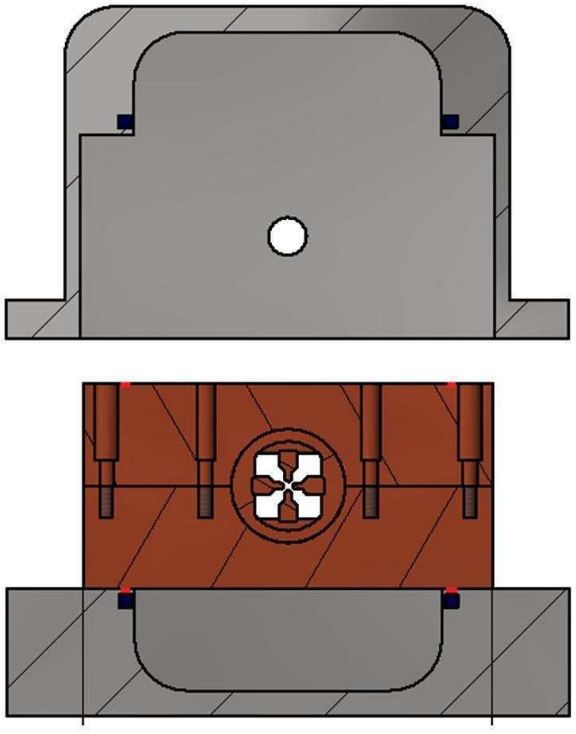


Geometric design parameters, dependence on frequency and Q-value

4-Ladder-RFQ







Mechanical design studies at IAP Frankfurt

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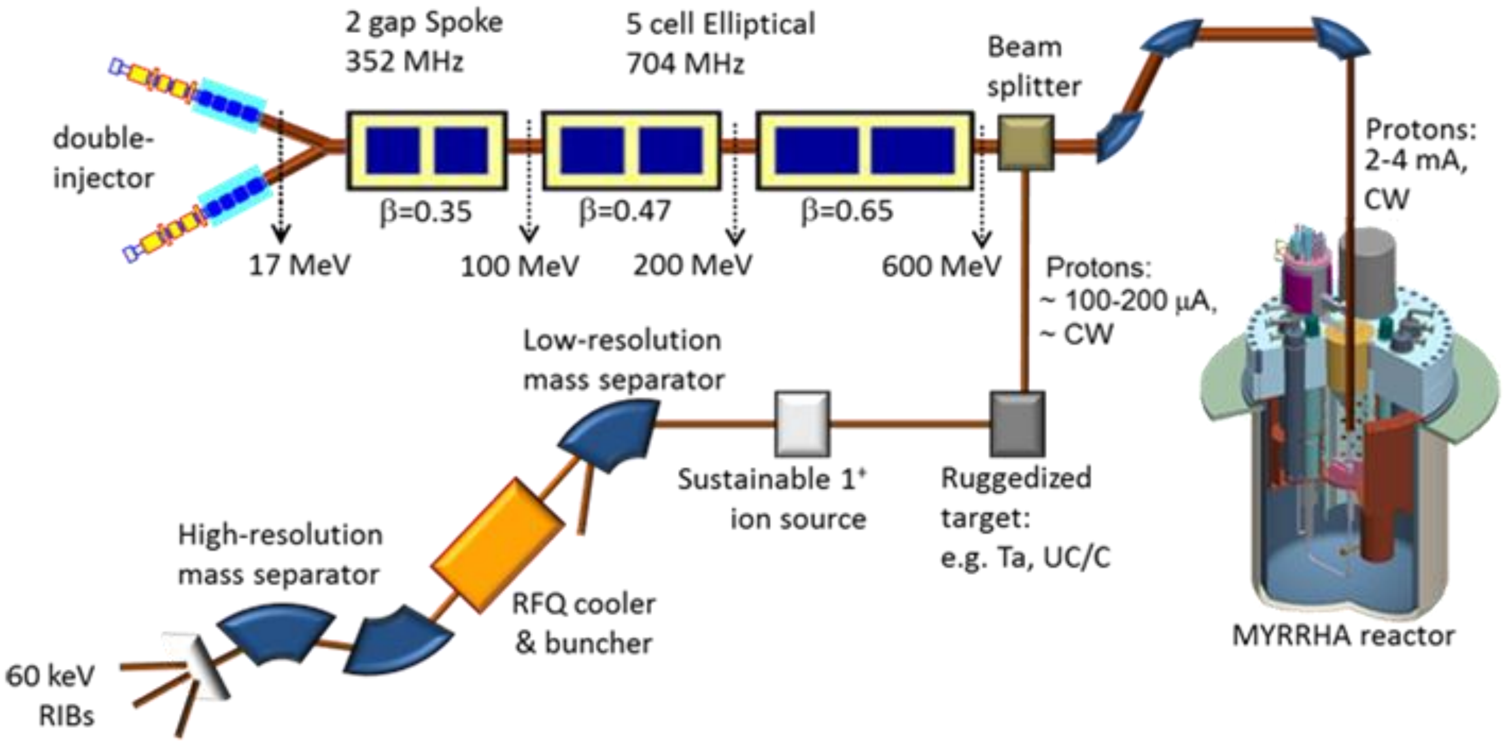
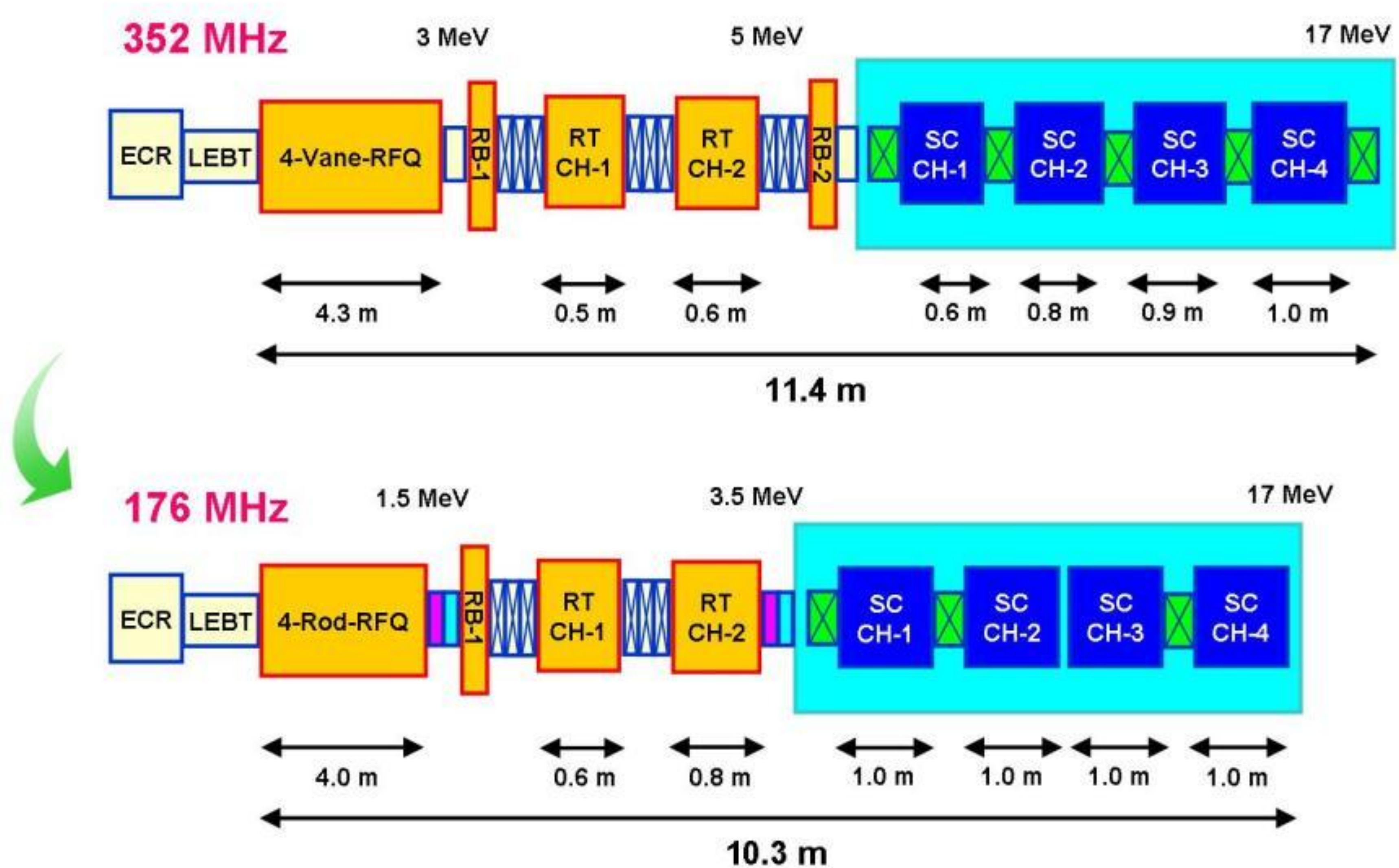
MYRRHA Project

Multi-purpose hYbrid Research Reactor for High-tech Applications At Mol (Belgium)



The European MYRRHA Project

Layout of the 17 MeV section designed by IAP



Conclusions

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- Many activities wordwide on linac development for fundamental research and for applications.
- Better performance of linac key components is one direction to go.
- Room temperature designs may gain attraction by new rf amplifier technology if pulsed beams are acceptable, rf duty factor up to 5%.
- FAIR Proton Injector development should demonstrate the capabilities of a novel approach.

Horst Klein, Celebration of his 80th Birthday

Fachbereich Physik
der Johann Wolfgang Goethe-Universität
Frankfurt am Main

Festkolloquium

anlässlich des 80. Geburtstages von
Prof. Dr. phil. nat. Horst Klein

Freitag, 28. Januar 2011, 16.00 Uhr s.t.
Hörsaal des Fachbereichs Physik
Max-von-Laue-Str. 1
60438 Frankfurt am Main

Moderation — Prof. Dr. Ulrich Ratzinger
Geschäftsführender Direktor
Institut für Angewandte Physik

Begrüßung — Der Dekan des Fachbereichs Physik
Prof. Dr. Michael Huth

Vorträge — Prof. Dr. Stephan Herminghaus
Direktor am Max-Planck-Institut für Dynamik und Selbstorganisation, Göttingen.
Georg-August-Universität, Göttingen
„Warum ist nicht nichts? Kollektive Phänomene fern vom thermischen Gleichgewicht"

Prof. Dr. Ingo Hofmann
GSI, Darmstadt
„Das nie enden wollende Energieproblem und was Beschleuniger dazu beitrugen"

Prof. Dr. Thomas Weis
TU Dortmund
„Wie wir die elektromagnetische Welle bändigten - ein Exkurs von der Wendel bis zu supraleitenden Vielzellern in der Beschleunigerphysik"

Grußworte — Prof. Dr. Dr. h.c. mult. Walter Greiner, FIAS

Prof. Dr. Wolfgang Grünbein, Präsident des Physikalischen Vereins

Anschließend gemütliches Beisammensein, Magistrale, 2. Stock.
Ihre Zusage hierzu senden Sie bitte an Frau Harji.
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