RF cavity for cost effective reliable, robust medical LINAC:
basic considerations

Outline

- Laurence Court 20 minutes
- Ivan Konoplev 40 minutes
- Paul Coe 15 minutes
  - Discussion

Outline

- Introduction
- RF power drivers:
  - Solid state power supply and Klystrons
  - Discussion
- RF cavity manufacturing techniques
  - Conventional disc and semi-cell manufacturing
  - Manufacturing from bulk material using CNC machining
  - Additive manufacturing for some components.
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- Material to manufacture the RF cavity and previous experience
  - Aluminium vs copper
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- Operating frequency: 1.3GHz, 3GHz, 6GHz, 9GHz, 12GHz
- Standing wave vs traveling wave
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- Servicing/Maintenance
- Costs

Technical Task Force

From a technical and systems perspective **stimulate innovation** in radiotherapy technologies and processes.

Near-term: Develop optimal design requirements for a novel high quality lower-cost treatment solution that leverages existing linac technologies and incorporates intelligent software designed for robust operation in a range of challenging environments. Such a system would be modular, rugged, easily operated, less reliant on personnel, and easily repaired but sufficiently sophisticated to also bring benefits to radiotherapy in high-income countries.

Long-term: Clearly identify shortfalls in existing critical subsystems (radiation production, power consumption, heat dissipation, automated maintenance, electromechanical collimation, imaging, safety, and training) and, through engagement of international technical centers of excellence, stimulate the development of next generation technologies to address these important needs.

RF Power Systems and Optimized RF structures for electron beam acceleration

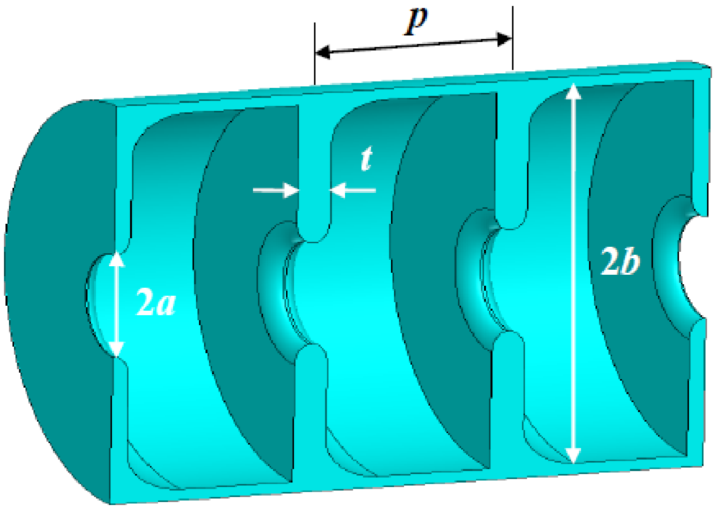
- Make it vacuum sealed as a single block - no vacuum pumps
- Consider alternative RF cavity manufacturing technology
- Consider Aluminium as an alternative material
- Make a suggestion for operating frequency
- Make it compatible with permanent magnet focusing system
- Make a suggestion for energy and current

Introduction: Some technical data

Frequency Range	Microwave / Radar Bands
216 — 450 MHz	P-Band
1 — 2 GHz	L-Band
2 — 4 GHz	S-Band
4 — 8 GHz	C-Band
8 — 12 GHz	X-Band
12 — 18 GHz	K_u-Band
18 — 26.5 GHz	K-Band
26.5 — 40 GHz	K_a-Band
30 — 50 GHz	Q-Band
40 — 60 GHz	U-Band
50 — 75 GHz	V-Band
60 — 90 GHz	E-Band
75 — 110 GHz	W-Band
90 — 140 GHz	F-Band
110 — 170 GHz	D-Band
110 — 300 GHz	mm-Band

American / European Frequencies

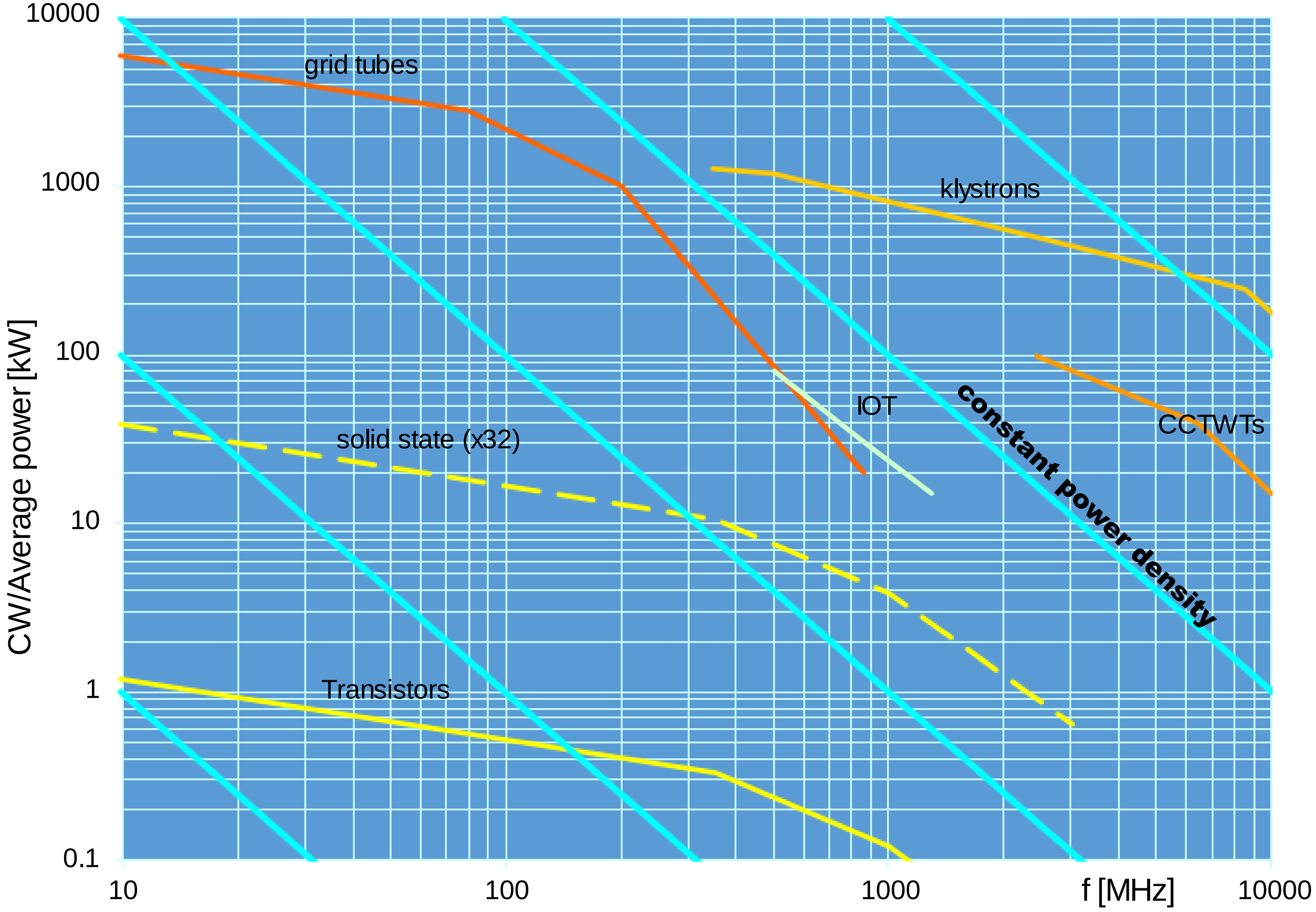
S-band : 2856 MHz / 2998 MHz
C-band : 5712 MHz / 5996 MHz
X-band : 11424 MHz / 11992 MHz



TW accelerating structure

RF power sources

Typical ranges (commercially available)

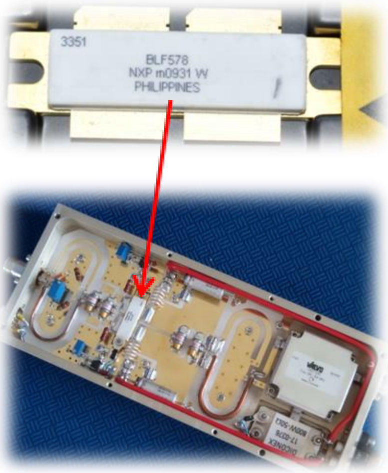


Typical limitation: power/energy density

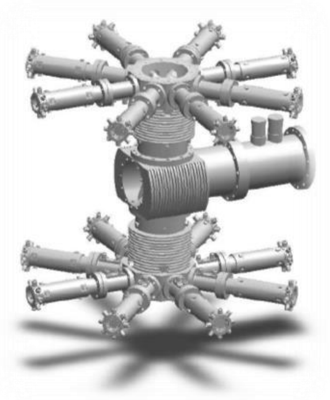
Soleil/ESRF Booster SSPA, 150 kW, 352 MHz

- Initially developed by SOLEIL
- Transfer of technology to ELTA / AREVA

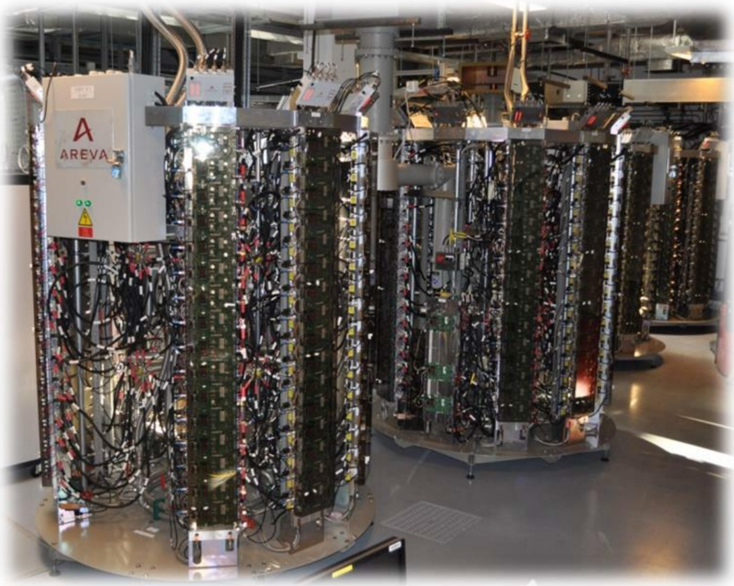
Pair of push-pull transistors



x 128



x 2



650 W RF module

- 6th generation LDMOSFET (BLF 578 / NXP), V_{ds} = 50 V
- Efficiency: 68 to 70 %

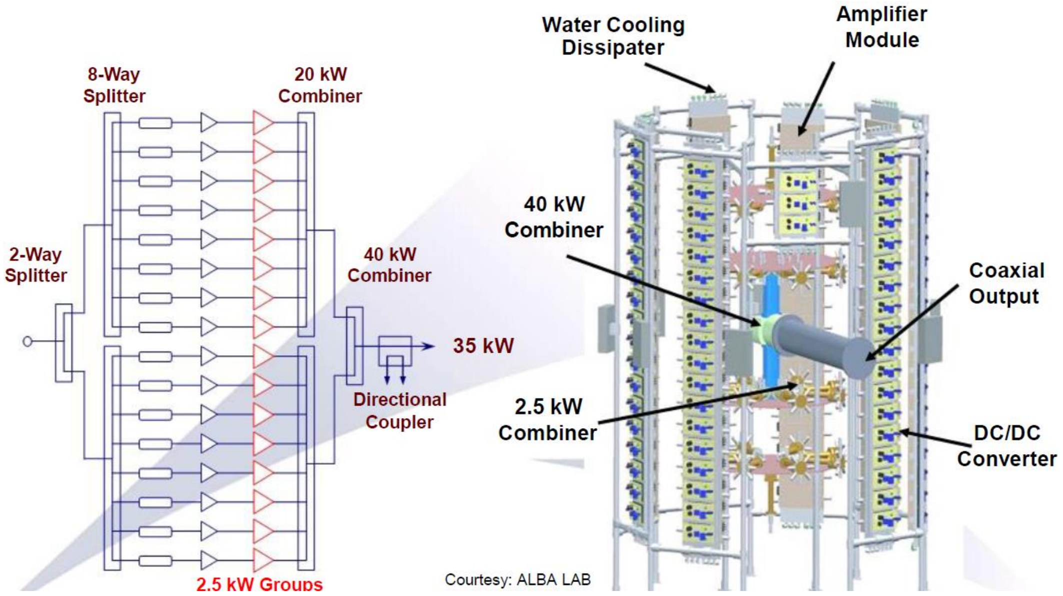
75 kW Coaxial combiner tree

with $\lambda/4$ transformers

150 kW, 352.2 MHz Solid State Amplifiers for the ESRF booster (7 in operation)

Efficiency: > 57 % at nominal power

Example of SSA RF power supplies



Courtesy: ALBA LAB

1. SMPS DC power supplies
2. Driver amplifier
3. RF amplifier modules
4. Input splitter
5. Output combiner
6. Directional Coupler
7. Interlocking & protection circuit

One of the most complicated parts are power combiner and cooling

Klystrons

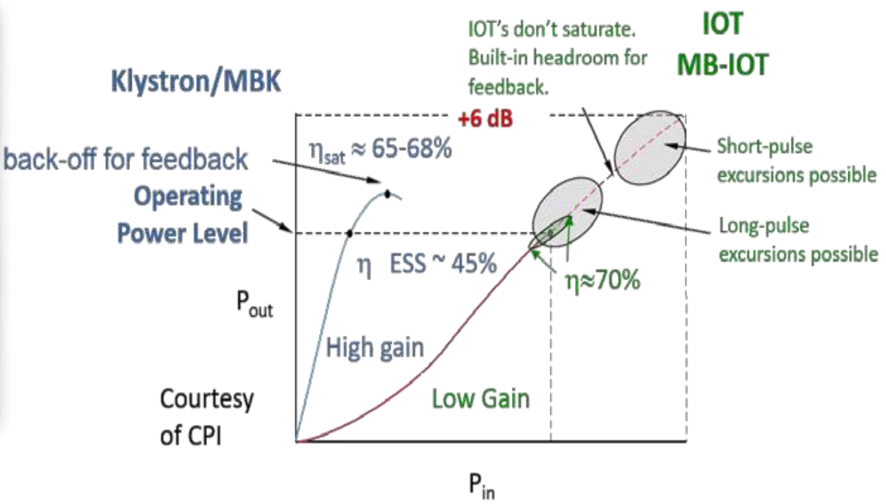
CERN CTF3 (LIL):
3 GHz, 45 MW,
4.5 μs, 50 Hz, η 45 %

CERN LHC:
400 MHz, 300 kW,
CW, η 62 %

RF power generators – efficiencies

	Tetrodes	IOTs (Inductive Output Tubes)	Conventional klystrons	Solid State PA	Magnetrons
f range:	DC – 400 MHz	(200 – 1500) MHz	300 MHz – 12 GHz	DC – 20 GHz	GHz range
P class (CW):	1 MW	1.2 MW	1.5 MW	1 kW @ low f	< 1MW
typical η:	78 %	70%	50- 73 %	60%	90%
Remark	Broadcast technology, widely discontinued		new idea promises significant increase	Requires P combination of thousands!	Oscillator, not amplifier!

Thales RS 1084 CJ
< 30 MHz, 75 kW
η< 78% (class B)



Courtesy of CPI

CLIC DB klystron
1 GHz, 20 MW, 15 0 µs,
50 Hz, η≈ 73%

RF power drivers

	Klystron	SSA
Efficiency	50%-70%	50%-70%
Frequency (GHz)	0.1 – 15	up to 1
Peak Power (MW)	Up to 10	<1
Stability	high	high
Life expectancy	high	high
Cooling	yes	yes
Maintenance	complex	simple
Size	compact	large
Mobility	yes	yes
Modularity	partial	yes
Capital Cost	high	high
Run Cost	intermediate	intermediate

Conclusion/Suggestion:

Short term (2-3 years) Solid State RF oscillator + Klystron Amplifire

- Broad frequency range availability
- Compactness of SSO and robustness of Klystron

Long term (over 5 years): Monitor SSO/A development at GHz frequency range

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RF cavity manufacturing techniques

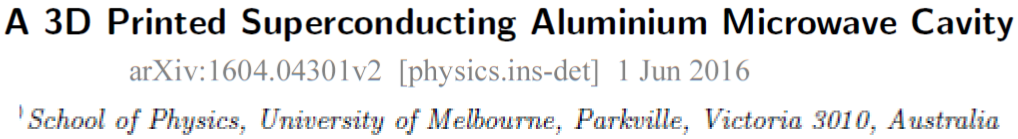
1/

Oxford, UH-FLUX project

3a/

Oxford, UH-FLUX project

2/



A 3D Printed Superconducting Aluminium Microwave Cavity

arXiv:1604.04301v2 [physics.ins-det] 1 Jun 2016

[1] *School of Physics, University of Melbourne, Parkville, Victoria 3010, Australia*

3b/

CERN, CLIC

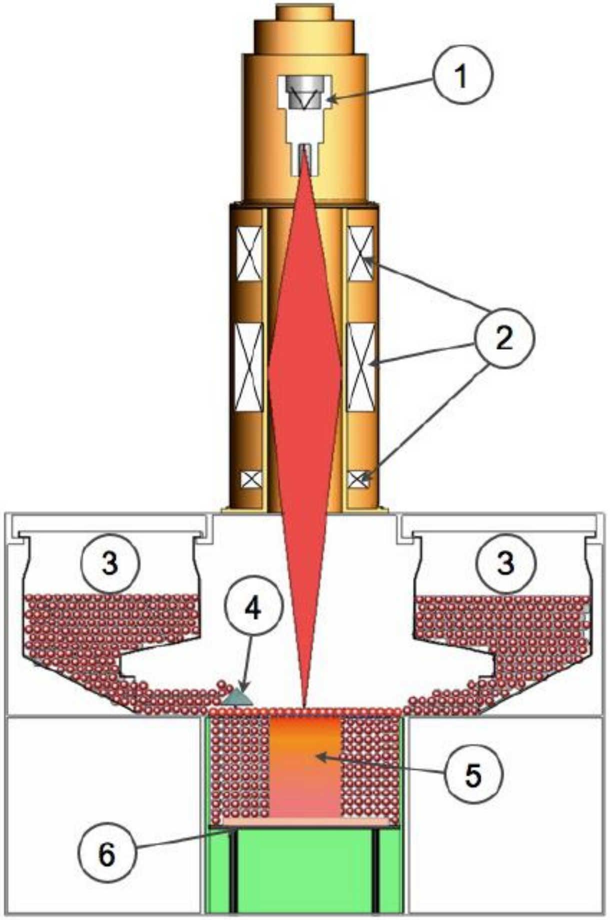
Additive manufacturing

- 3D printing in Titanium for lossy parts like loads or low power components
- Parallel development at CERN and in industry
- SWISSto12 (CH), 3T RPD (UK), Concept Laser (DE), INITIAL (FR), Protoshop (DE)
- Currently under test for high power operation. Very promising results!

Prototype of SRF cavity, JLab, Radiabiam

New technology can be used for some parts: aluminium or titanium

Additive manufacturing

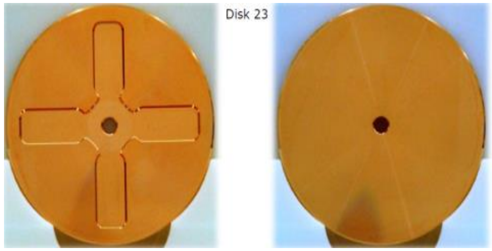


Metal powder (30μm – 120μm diameter), contained in two stainless steel hoppers (3), is gravity fed to a raking mechanism (4) which spreads the powder forming a uniform layer on a vertically adjustable platform (6). An electron beam (e-beam), generated by a thermionic cathode (1), is accelerated to a typical energy of 60 keV. The e-beam is collimated and steered by magnetic optics (2), and used to pre-heat the entire powder layer (50-120μm) with a combination of low beam current and high scan speed.

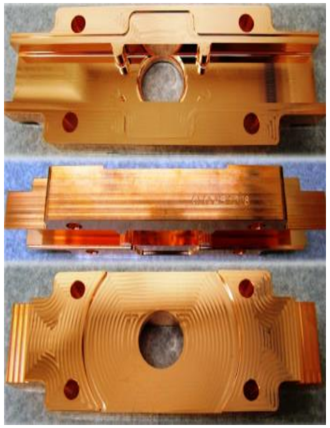
Proceedings of SRF2015, Whistler, BC, Canada THPB042

Manufacturing discs and half cells

TD26 CC discs

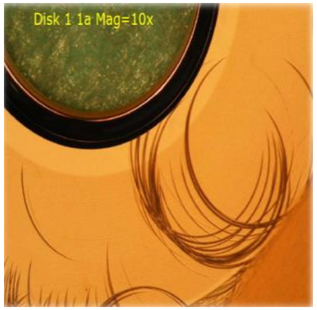


TD24 R05 couplers

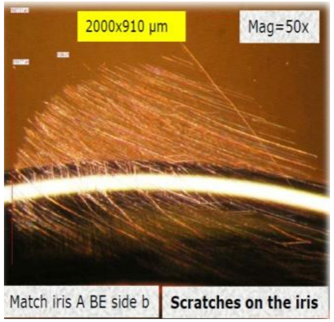


Machining defects

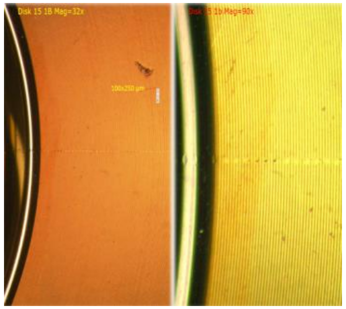
1. Milling marks in turning area



2. Scratches in RF area



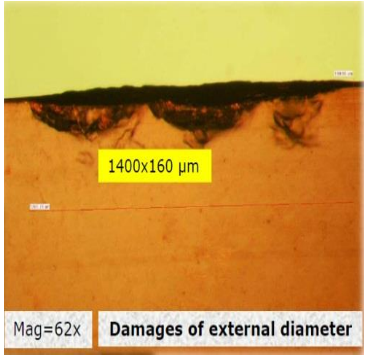
3. indents/caverns in RF area



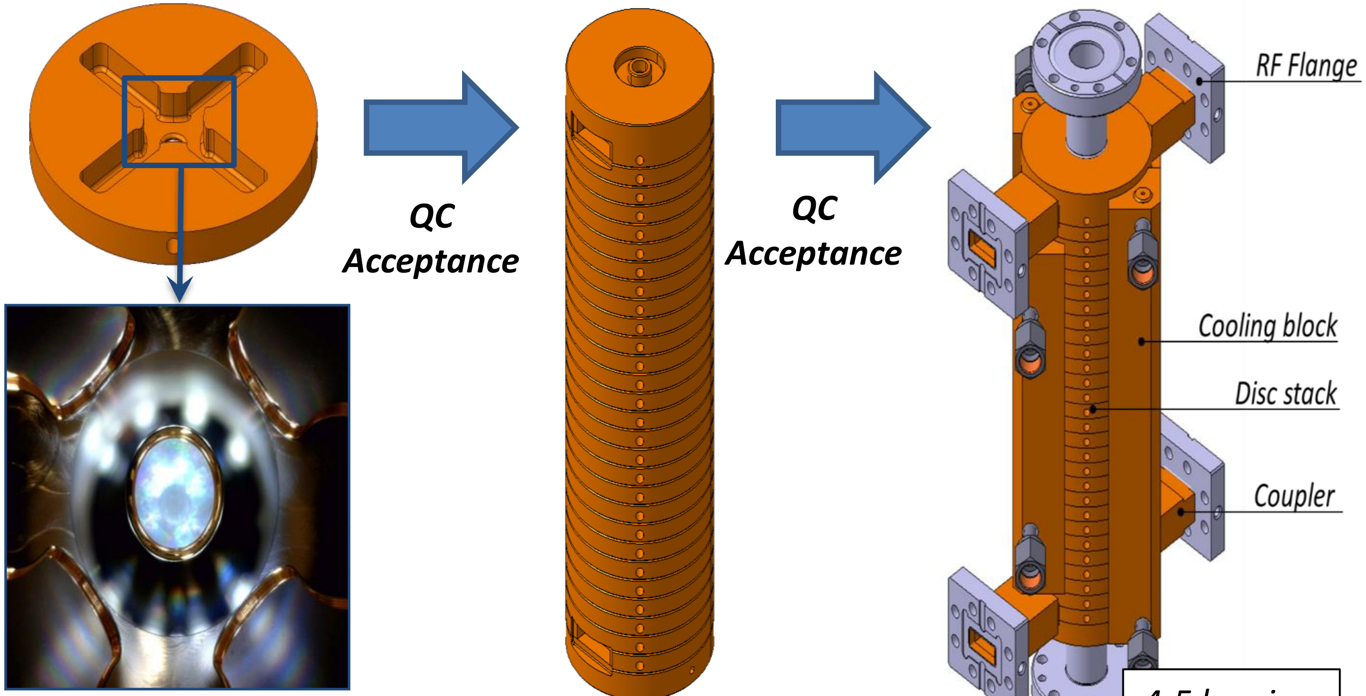
4. Burrs in sharp edges

Andrey Olyunin
Nerea Mouriz Irazabal

5. Damages on external diameter



Structure manufacturing



DISC

QC Acceptance

DISC STACK BONDING

QC Acceptance

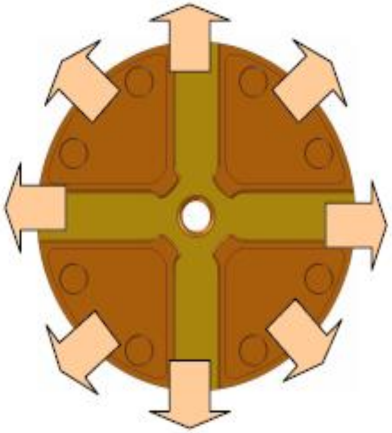
ASSEMBLY

4-5 brazing steps

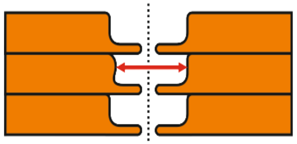
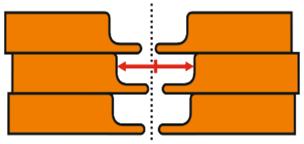
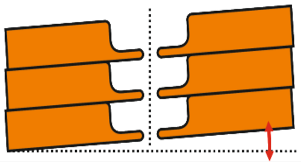
Manufacturing Challenges

Asymmetrical heating or weight application

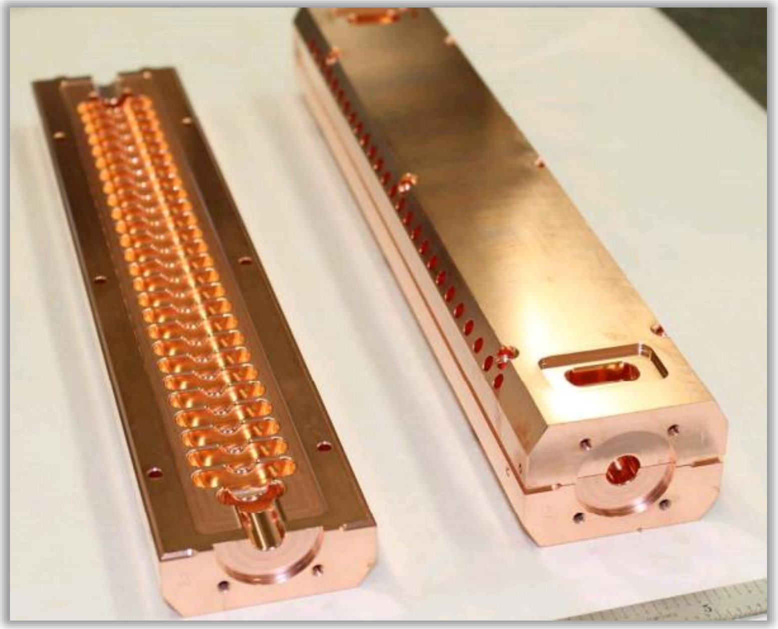
Extension → difficulties in assembling with another parts



Misalignment (due to alignment and machining tolerances)

	Error in iris shape	Transversal offset	Tilt
Shape error			
Tolerance	1 µm [2,5]	5 µm [3]	140 µrad [2,5]

Manufacturing using CNC lathe machining



Good:
Surface preparation and conditioning
EM properties
Cost effective
Easy aligning and quality control

Challenges:
Vacuum sealing
Design of asymmetric geometries

Solutions/suggestions

1/ Manufacture from bulk material using CNC lathe

2/ Use additive technology (if cheaper and more reliable) to manufacture components outside vacuum envelop

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Material to manufacture the RF cavity Copper Vs Aluminium

Property	**Copper(Cu-ETP)**	**Aluminium(1350)**	**Units**
Electrical resistivity (annealed)	**1.72**	**2.83**	**mOhm-cm**
Thermal conductivity at 20°C	**397**	**230**	**W/mK**
Coefficient of expansion	17 x 10-6	23 x 10-6	/°C
Tensile strength (annealed)	200-250	50-60	N/mm2
Tensile strength (half-hard)	260-300	85-100	N/mm2
0.2% proof strength (annealed)	50-55	20-30	N/mm2
0.2% proof strength (half-hard)	170-200	60-65	N/mm2
Elastic modulus	116-130	70	N/mm2
Fatigue Strength (annealed)	62	35	N/mm2
Fatigue Strength (half hard)	117	50	N/mm2
Specific heat	385	900	J/kgK
Density	**8.91**	**2.70**	**g/cm3**
Melting Point	**1083**	**660**	**°C**

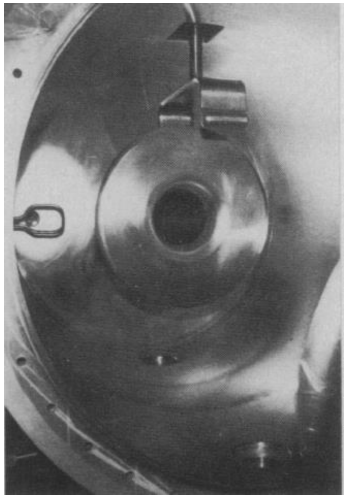
Copper (MT)	**$6923**	**Aluminium (MT)**	**$2069**

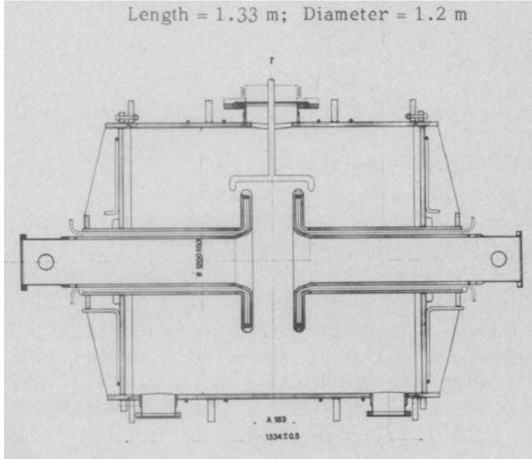
Use of Aluminium

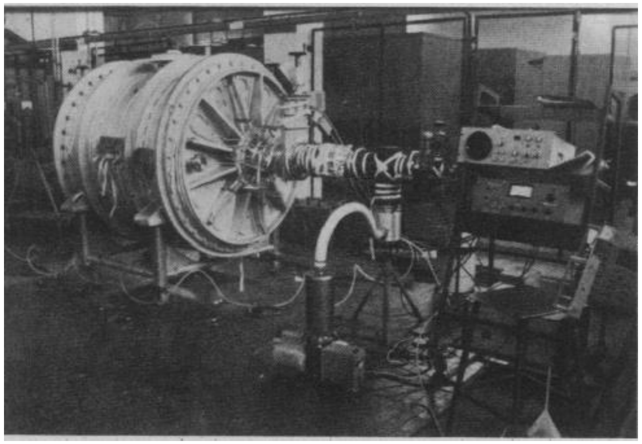
- First found publication IEEE Transaction Nucl. Science NS30(4), p3566, 1983 - RF cavity at 51MHz (vacuum compatible)
  - Recipe: cleaned with acid solution (1% HCl+nitric) after machining and rinsed with organic detergent (Methyl-ethyl-keton); roughing pump and outgassing at 100C with pressure reached 5x10^{-9} Torr

  A number of aluminium RF cavities at different frequencies were designed and installed

  - The main problem is multipacting



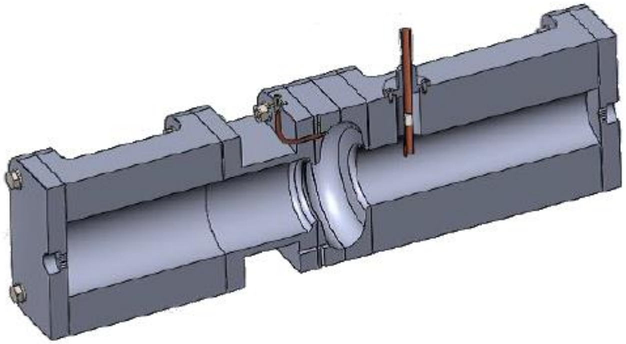




[1] A Gallo, et al. (INFN, Frascati, Italy), Intern. Workshop on Collective effects and impedances for B-factories, Tsukuba, Japan, June 1995
[2] Ya. V. Shashkov, et al. (INFN, Frascati, Italy), J. of Physics: Conf. Series, 747, 012088, 2016

Use of Aluminium: single cell RF cavity

Ya. V. Shashkov, et al. (INFN, Frascati, Italy), J. of Physics: Conf. Series, 747, 012088, 2016



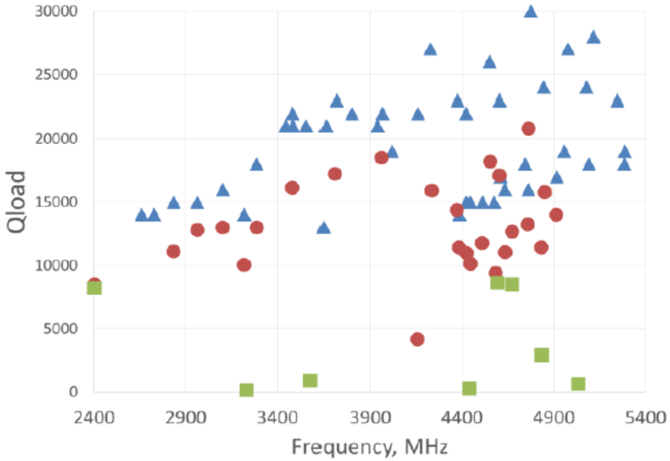


Figure 2. Q values of the cavity with a grooved beam pipe. Triangles – Q_0 calculation, circles - Q_0 measurements, square - Q_{load} measurements

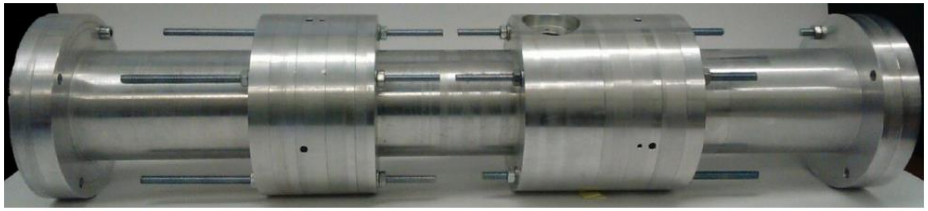
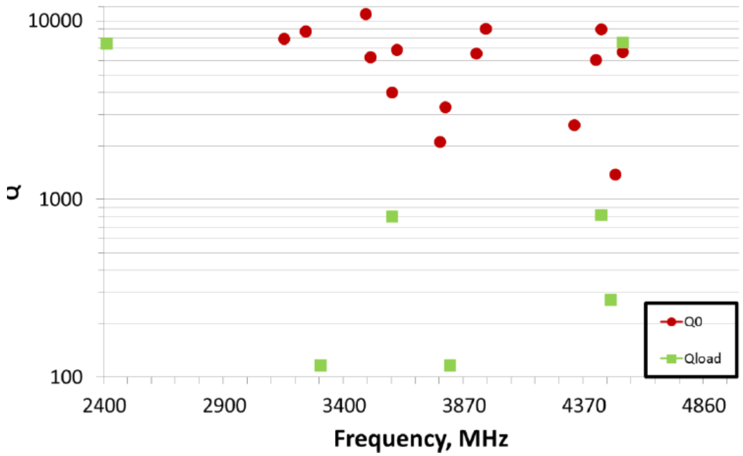


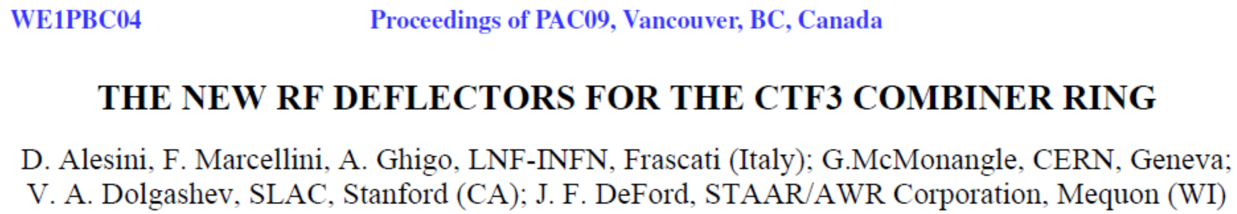
Figure 3. General view of the assembled prototype



. Q_{load} of the array of two cavities with a grooved beam pipe. Circles - Q_0 measurements, square - Q_{load} measurements

Use of Aluminium

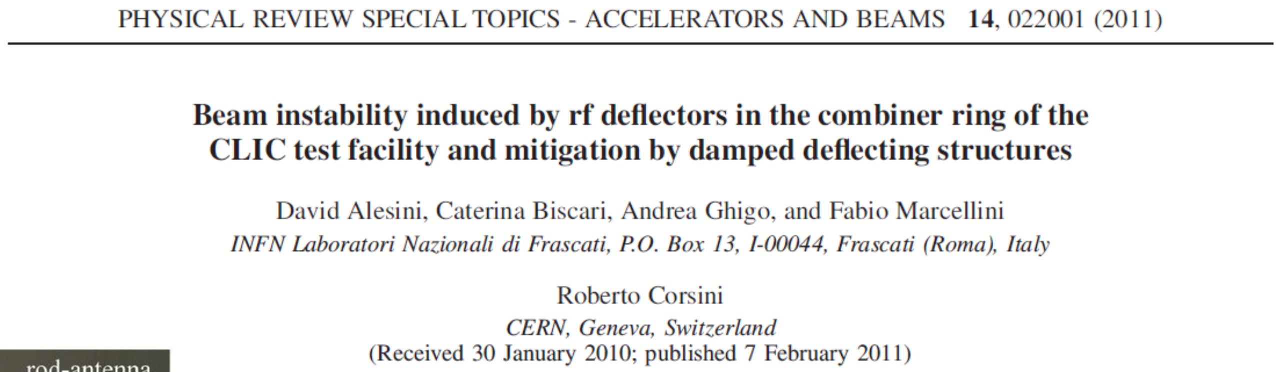
RF deflector for the CTF3 combiner Ring (Frascati, SLAC, CERN)



WE1PBC04 Proceedings of PAC09, Vancouver, BC, Canada

THE NEW RF DEFLECTORS FOR THE CTF3 COMBINER RING

D. Alesini, F. Marcellini, A. Ghigo, LNF-INFN, Frascati (Italy); G.McMonangle, CERN, Geneva;
V. A. Dolgashev, SLAC, Stanford (CA); J. F. DeFord, STAAR/AWR Corporation, Mequon (WI)

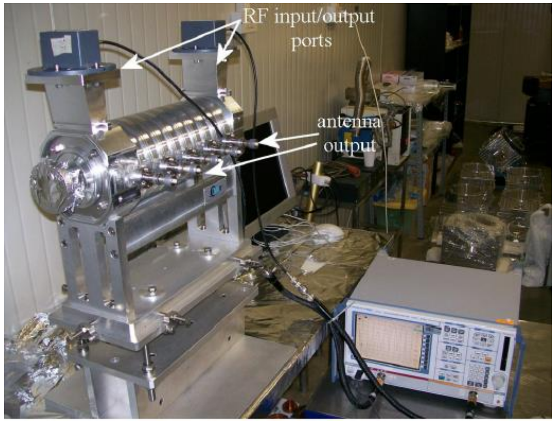


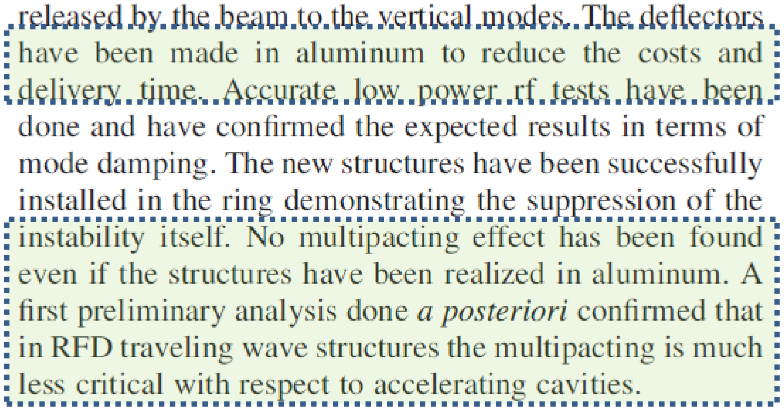
PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS **14**, 022001 (2011)

Beam instability induced by rf deflectors in the combiner ring of the CLIC test facility and mitigation by damped deflecting structures

David Alesini, Caterina Biscari, Andrea Ghigo, and Fabio Marcellini
INFN Laboratori Nazionali di Frascati, P.O. Box 13, I-00044, Frascati (Roma), Italy

Roberto Corsini
CERN, Geneva, Switzerland
(Received 30 January 2010; published 7 February 2011)





released by the beam to the vertical modes. The deflectors have been made in aluminum to reduce the costs and delivery time. Accurate low power rf tests have been done and have confirmed the expected results in terms of mode damping. The new structures have been successfully installed in the ring demonstrating the suppression of the instability itself. No multipacting effect has been found even if the structures have been realized in aluminum. A first preliminary analysis done *a posteriori* confirmed that in RFD traveling wave structures the multipacting is much less critical with respect to accelerating cavities.

Conclusion/suggestions

1/ The physical properties of copper is superior to aluminium.

2/ Aluminium advantage: cost and weight

3/ Shifting to high frequency reduces the aluminium advantages and makes copper price competitive

4/ Multipacting can be issue in case of aluminium

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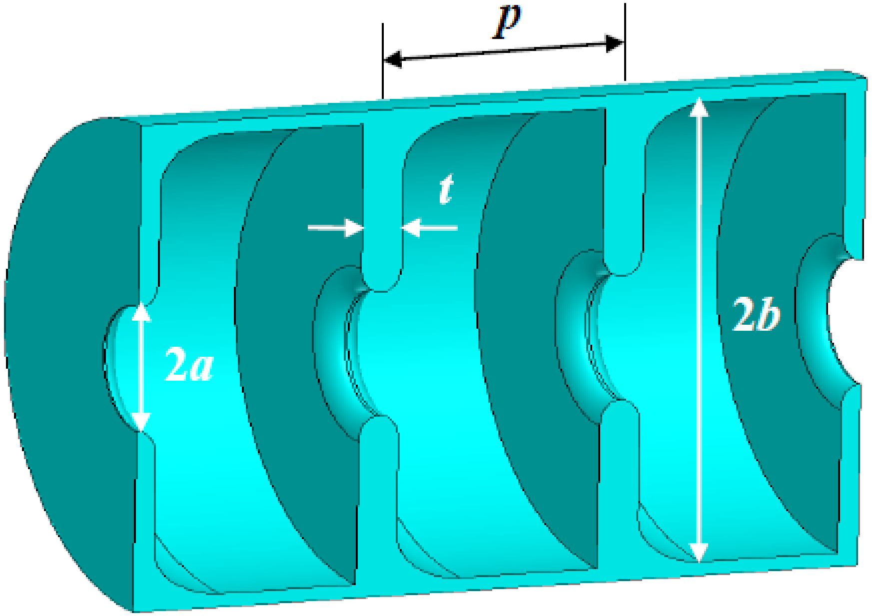
Operating frequency:
1.3GHz, 3GHz, 6GHz, 9GHz, 12GHz

- Solid State RF oscillator + Klystron Amplifire
- Shifting to high frequency reduces the aluminium advantages and makes copper price competitive and more attractive
- Manufacturing using CNC lathe machining
- Decreasing dimensions (high operating frequency) makes design of permanent magnets electron –beam optical system less complex

S-band TW Linac Structure

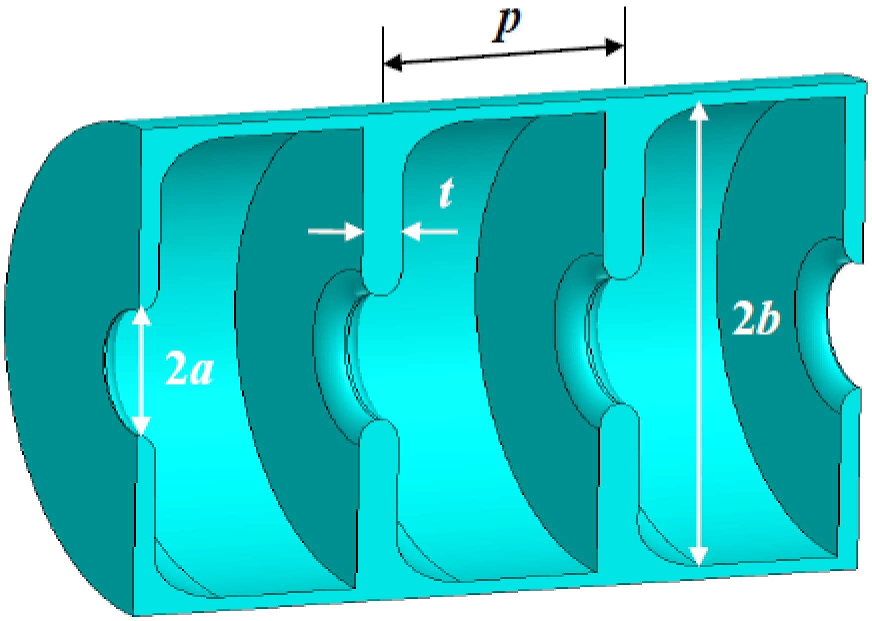


Schematic of TW accelerating structure

RF Frequency = 2997.924 MHz
average inner diameter 2*a* = 22.005 mm
average outer diameter 2*b* = 80.302 mm
period *p* = 33.333 mm
iris thickness *t* = 5 mm

Single cell dimension 35.25 mm
Expected gradient 22MV/m
Expected total length ~ 400 mm
Expected weight M_{cu} < 10kg
Expected weight M_{al} < 3kg

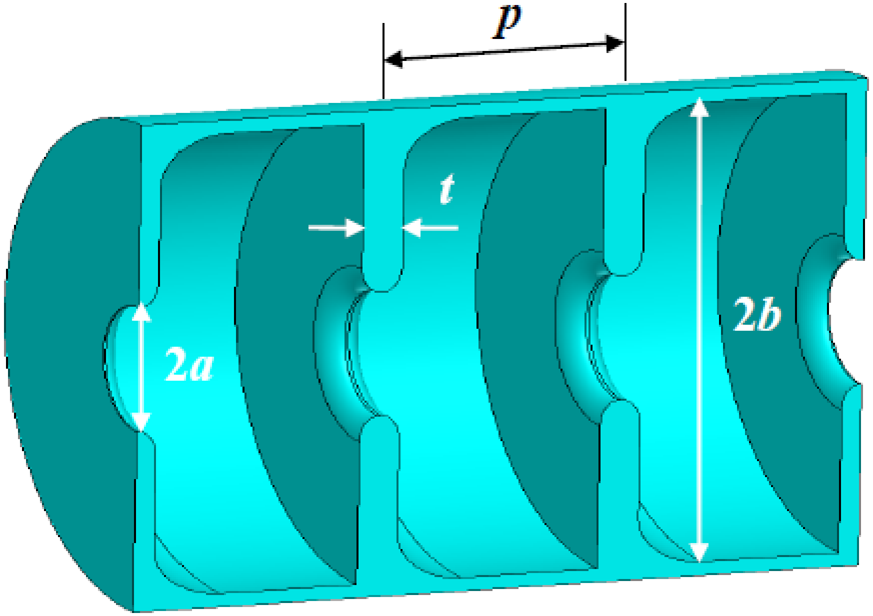
C-band TW Linac Structure



Schematic of TW accelerating structure

RF Frequency = 5712MHz
Average inner diameter 2a = 15mm
Average outer diameter 2b = 45mm
Iris thickness t = 3mm
Period p = 19.7mm
Expected gradient 30MV/m
Expected total length ~ 300 mm
Expected weight M_{cu} < 4kg
Expected weight M_{al} < 1.3kg

X-band TW Linac Structure



Schematic of TW accelerating structure

- average iris diameter $2a$: 9.1 mm
- average outer diameter $2b$: 21.4267 mm
- cell length p: 10.4104 mm
- iris thickness t : 1.6963 mm

RF Frequency = 11991.648MHz
Expected gradient 40 MV/m
Expected total length ~ 250 mm
Expected weight M_{cu} < 1kg
Expected weight M_{al} < 0.3kg

Conclusion/suggestions

1/ If schema SSOsc + Klystron is used to drive Linac we can consider high frequency C- band options 6GHz or 9GHz. The price of klystron and SSOsc will be the defining

2/ Low frequency less manufacturing cost

3/ High frequency Linac will be more compact

4/ Availability of 6GHz or 9GHZ test equipment at CERN

5/ At high frequency electron beam optics seems to be less chalenging

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- Costs

Standing wave vs travelling wave

- At high frequency to avoid multipacting and use technology available TW Linac seems to be appropriate.
- At frequencies 1.3GH and below standing wave system can be considered.

Outline

- RF power drivers:
  - Solid state power supply and Klystrons
  - Discussion
- RF cavity manufacturing techniques
  - Conventional disc and semi-cell manufacturing
  - Manufacturing from bulk material using CNC machining
  - Additive manufacturing for some components.
  - Discussion
- Material to manufacture the RF cavity and previous experience
  - Aluminium vs copper
  - Discussion
- Operating frequency: 1.3GHz, 3GHz, 6GHz, 9GHz, 12GHz
- Standing wave vs travelling wave
  - Discussion
- Servicing/Maintenance
- Costs

Servicing, maintenance, cost

- Vacuum sealed (no external pump)
- Cathode incorporated with Linac and changed with the Linac.
- Modular design: change parts without service

Thank you