Twin-Axis Elliptical Cavity

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ERL Workshop, 18-23 June 2017, CERN

Principle Idea

- Twin-axis elliptical cavity can accelerate and decelerate beams in two separate beam pipes
  - Energy recovery feasible of physically separated beams traversing the same cavity
- Primary idea of proposal for twin-axis cavity was that the low energy (vulnerable) beam from the electron source has to be merged with high-energy (spent) beam
  - Twin-axis cavity allows injecting the beam without requiring bends (no complex merger magnet) as beams are separated physically
  - Allows maintaining small emittance from source (high brightness)
- Second idea related to the ability to dump beam without an intervening bend thus containing beam size (otherwise large energy spread and emittance of decelerated beam)
  - Improve feasibility of recovering energy of otherwise fully dumped beam
    → out-couple RF power, e.g. feed back to injector
  - Ease dump design, i.e. energy can be lowered to minimize activation
- Usable for high-current, low energy electron beams for bunched beam cooling of high-energy protons or ions (JLEIC cooler ERL)

Funding Opportunity

- Funding for this project provided by the US DoE Office of High Energy Physics as part of an Accelerator Stewardship Test Facility Pilot Program ("ASTFPP") initiated in 2015
- Mission of long-term accelerator R&D stewardship program is to
  - Support fundamental accelerator science and technology R&D
  - Disseminate accelerator knowledge and training
- The new ASTFPP specifically endorses access to the Office of Science accelerator R&D infrastructure
- Pre-requisite of the stewardship program was partnering with a university (in our case ODU/CAS) and engaging a graduate student in the research
- Our proposal was award in August 2015 for a one-year duration
- Work effort required beyond the one year period is based on no-cost extension
- No follow-up phase was permitted through same stewardship program

Objective

- Design, optimize, and build a novel twin-beam axis superconductive RF cavity prototype (single-cell) for ERLs
- Prototype is **proof-of-principle of technical feasibility**
- To our knowledge this is the first twin-axis cavity built despite past, similar proposals and conceptual design studies
- Operational mode conceived is a dipole HOM (TM_{110}-like)
  - Requires to symmetrize RF fields in beam tubes by design
  - Minimization of higher order multipole components of operating mode needed that can cause residual kick to electrons even when beams traverse on ideal tube axis
- Further design/practical goals:
  - Target a rather large separation of the beam tubes
  - Limit surface field enhancement ratios (E_{acc}/E_{pk}, B_{pk}/E_{acc}) to acceptable values
  - Achieve acceptable R/Q and R/Q·G (cryogenic losses)
  - Assess (to some extent) potential multipacting barriers and structural integrity
  - Gain fabrication experience while using conventional, readily applicable techniques, i.e. forming of Nb sheets into half cells, rolling of beam tubes and join all components by electron-beam welding (EBW)
  - Frequency chosen is 1.5 GHz (JLab/CEBAF), but design scalable to any frequency

Past Proposals

- Potential of multi-beam axis cavities for ERLs identified early (KEK - SRF 2003)
  - Lower the beam energy in the injector
  - Avoid a complex injection beam line and optics
  - May allow to increase charge/current maintaining low beam emittance
  - Deliver beam to ERL and FEL simultaneously
- Squeezing the center of twin-axis cavity provides better balance of RF fields around two beam axes (favors weakly coupled structure, but not simple to press)
- Later conceptual design (ANL - ERL 2007) using two more interleaved cavities

MULTI-BEAM ACCELERATING STRUCTURES

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KEK, High Energy Accelerator Research Organization
1-1 Oho, Tsukuba, Ibaraki, 305-0801, Japan

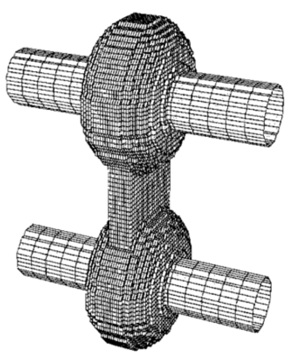


Figure 1: An example of single cell two-beam structures.

Table 1: Parameters of single cell two-beam structures

Type	Mode	Frequency	R / Q	Esp / Eacc	Hsp /Eacc	Geometrical Factor
		MHz	Ω		Oe / MV / m	Ω
Race Track	TM-110	750	33	3.4	100	180
	TM-210	940	57	2.1	56	250
Strong Couple	TM-110	705	18	7.2	207	106
Y=25, Z=4cm	TM-210	996	55	1.9	49	210
Medium Couple	TM-110	906	39	4.0	130	150
Y=16, Z=4cm	TM-210	990	59	1.9	43	230
Weak Couple	TM-110	994	54	1.9	57	226
Y=10, Z=4cm	TM-210	1000	63	1.9	40	237

TM-110 mode is monopole mode (TM010-like)
TM-210 mode is operational mode (TM110-like)

Proceedings of ERL07, Daresbury, UK

DUAL-AXIS ENERGY-RECOVERY LINAC*

Chun-xi Wang†, John Noonan, John W. Lewellen‡
Argonne National Laboratory, Argonne, IL 60439, USA

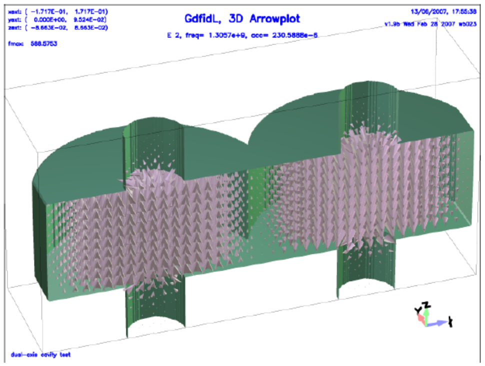
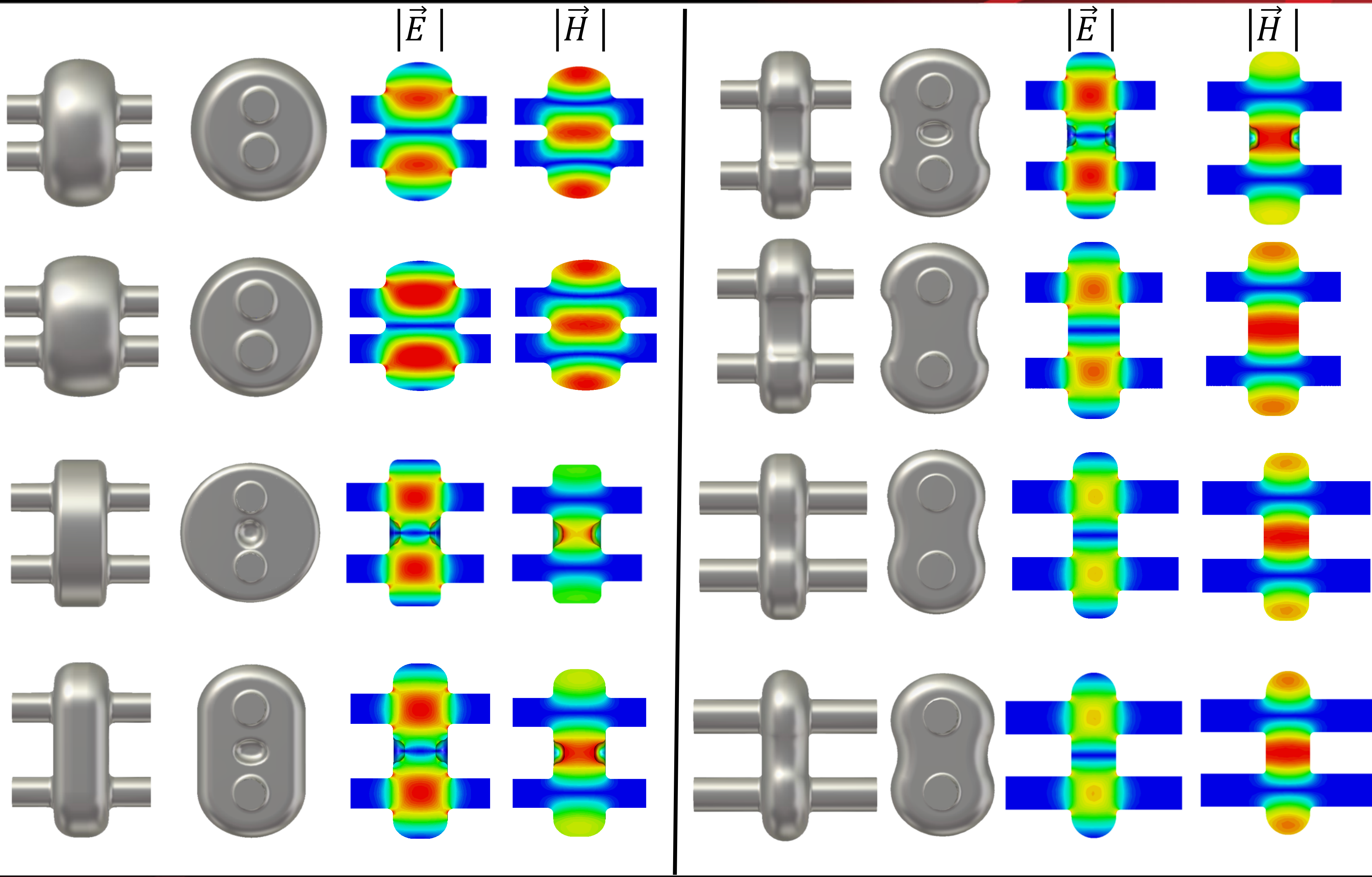


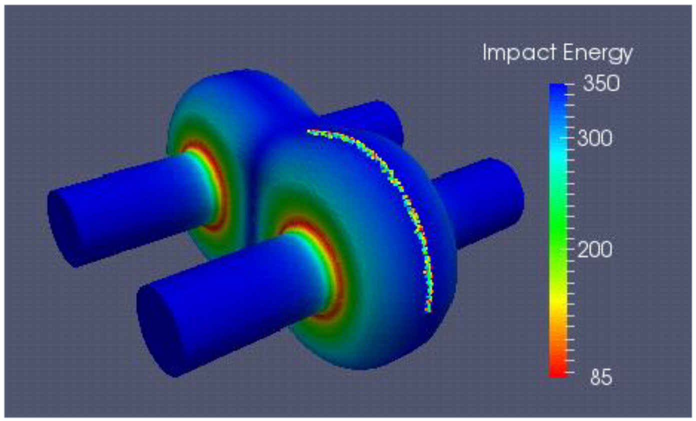
Fig. 1: A conceptual dual-axis single-cell cavity.

Design Evolution

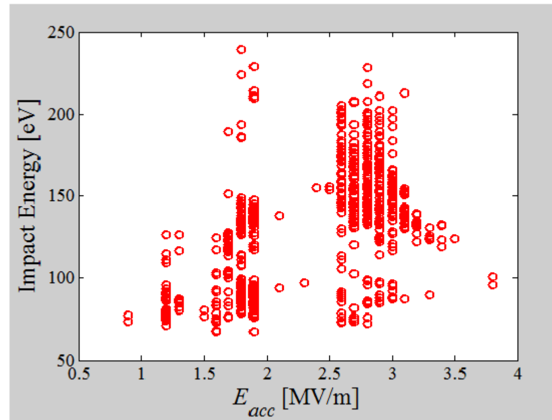


Multipacting (MP) Studies

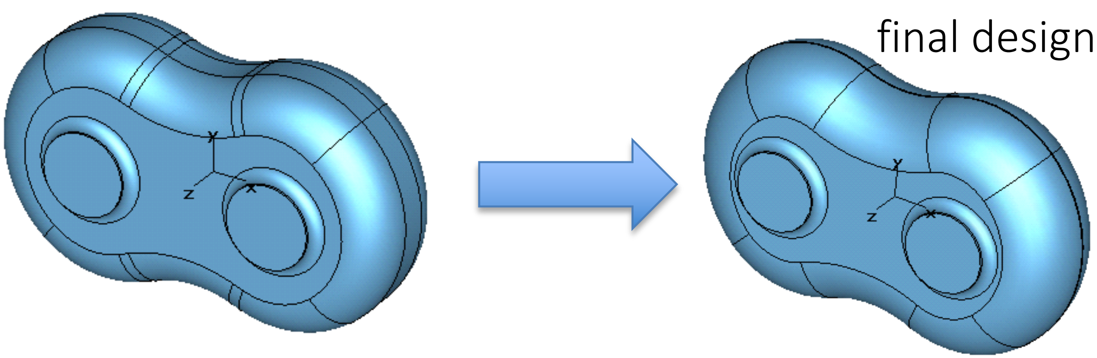
- E_{acc} = 15 MV/m is an envisioned operating field
- 3D ACE3P/Track3P resonant MP studies performed up to E_{acc} = 16 MV/m
  - Electron impact energy range of 50-2000 eV considered



Electrons with resonant MP trajectories at cell equator (impact energy in eV)



Impact energy of electrons surviving 50 RF cycles. MP barrier below E_{acc} = 4 MV/m

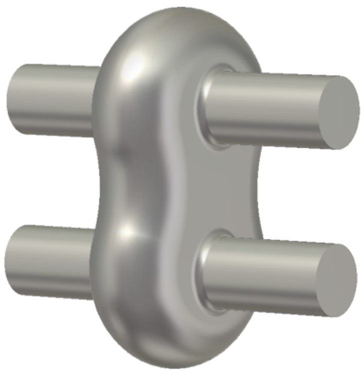


final design (increase equator axis)

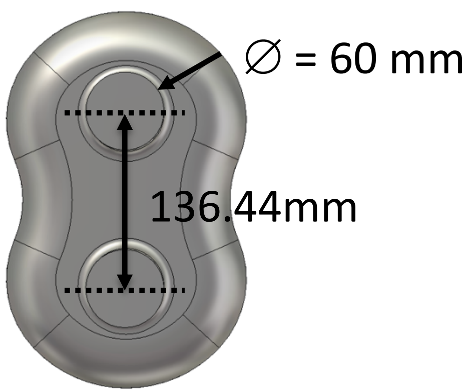
MP barrier below 4 MV/m vanished (MP barrier beyond 16 MV/m still possible)

Final RF Design

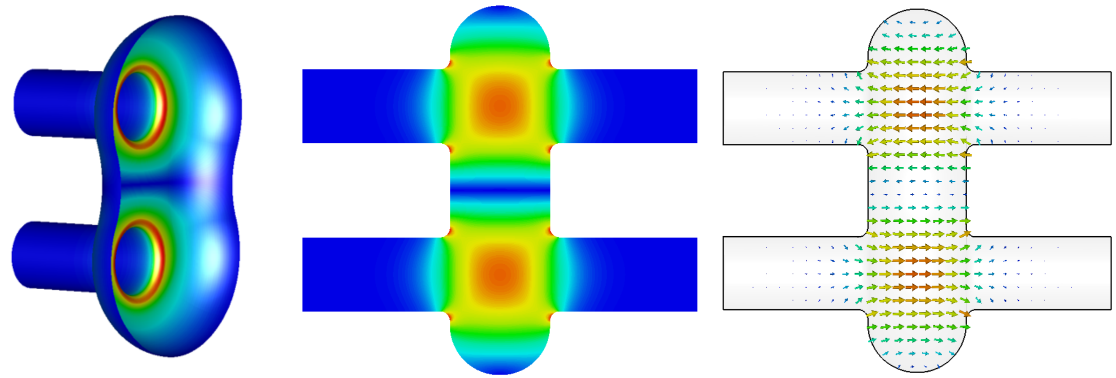
- Transverse field components of operating mode minimized at beam tube centers
- Beam tubes slightly shifted off the peak electric field to cancel dipole effect



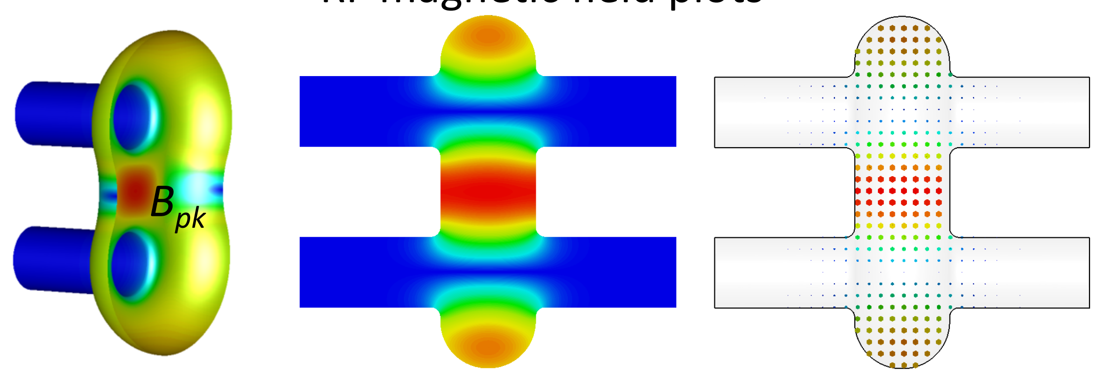
1.5 GHz design



RF electric field plots

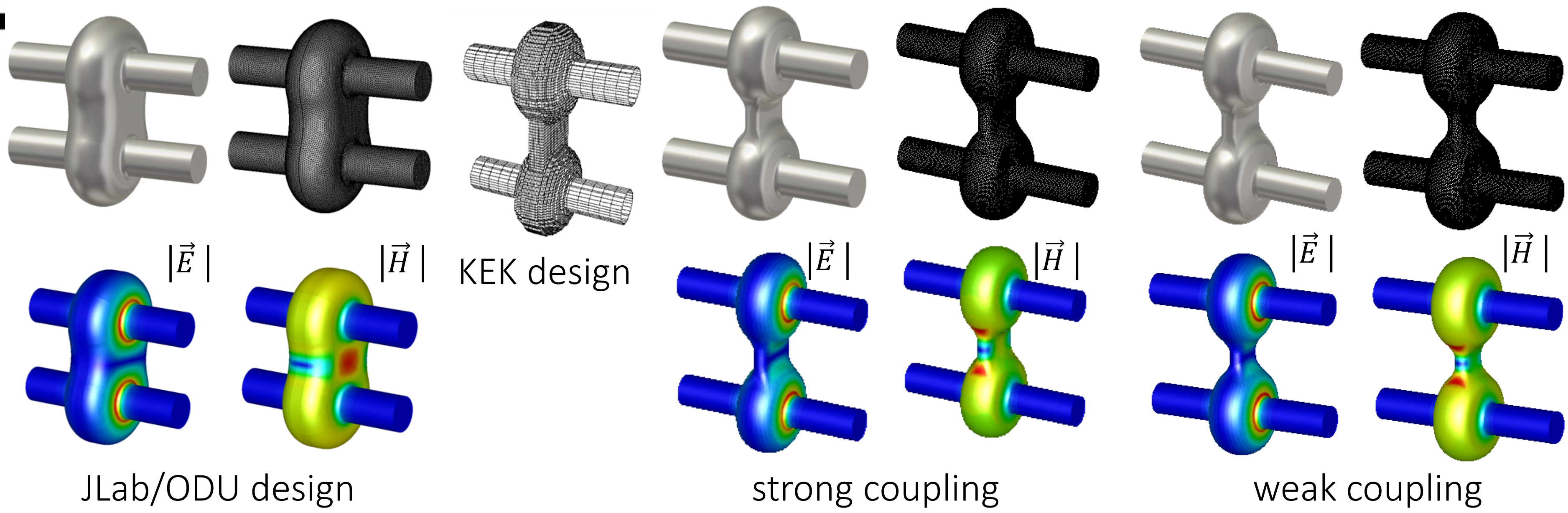


RF magnetic field plots



@ E_{acc} = 15 MV/m → B_{pk} = 78.9 mT

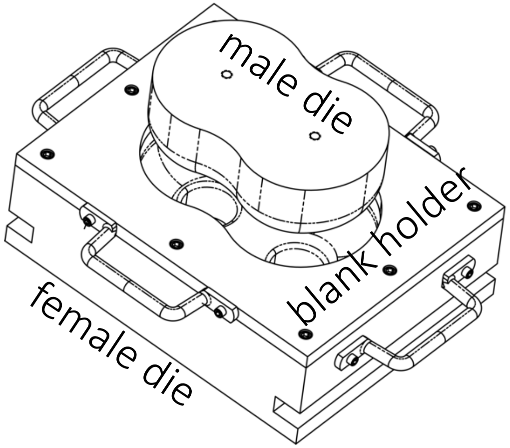
Design Parameters - Comparison

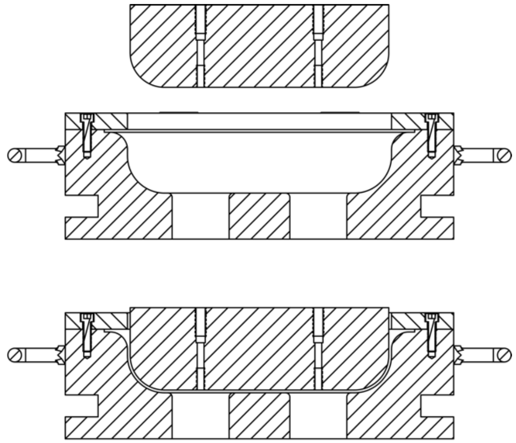


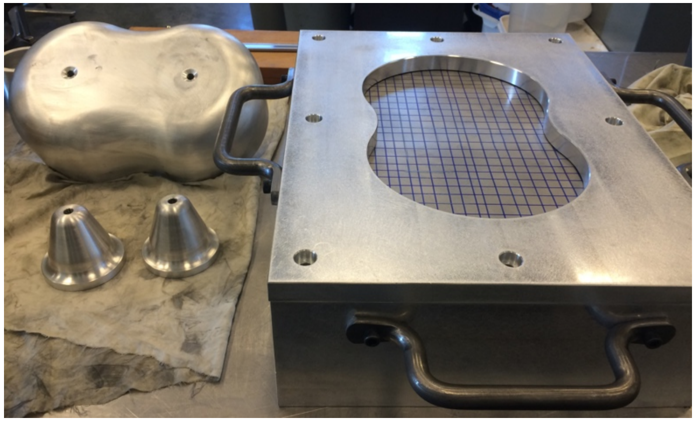
Parameter		New JLab/ODU Design
Operational mode		TM110
E_{pk}/E_{acc}		2.33
B_{pk}/E_{acc}	$mT\cdot(MV/m)^{-1}$	5.26
R/Q – US def.	Ohm	61.8
G	Ohm	313.8
R/Q·G	Ohm^2	19377

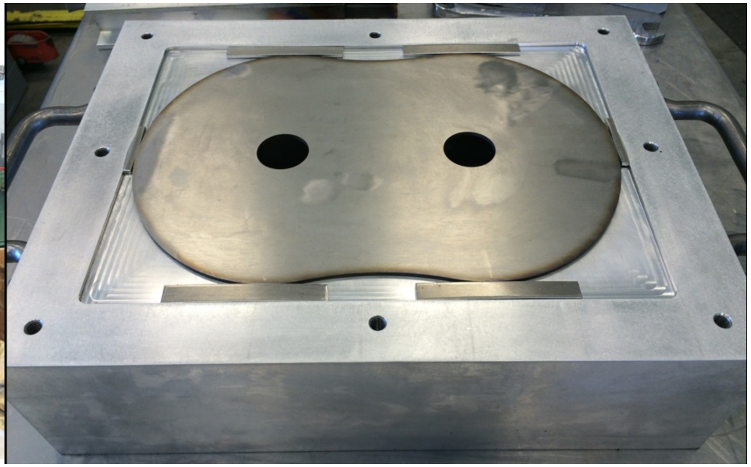
Deep-Drawing of Half Cells

- Deep-drawing study done with Al and Cu discs (1/8” = 3.175 mm thick material)

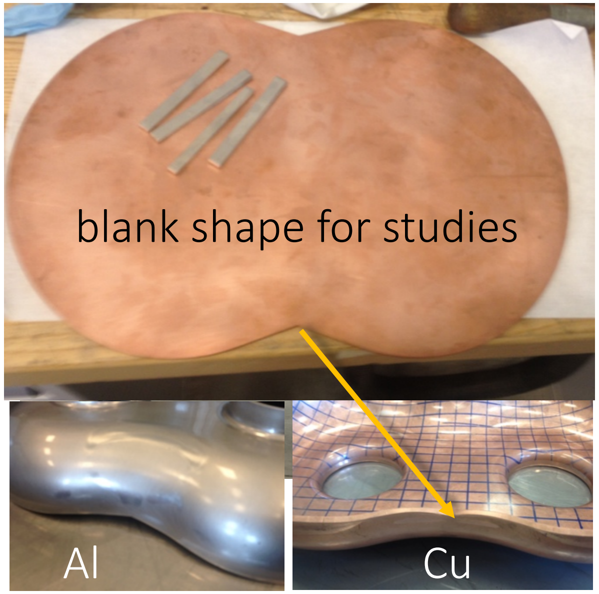




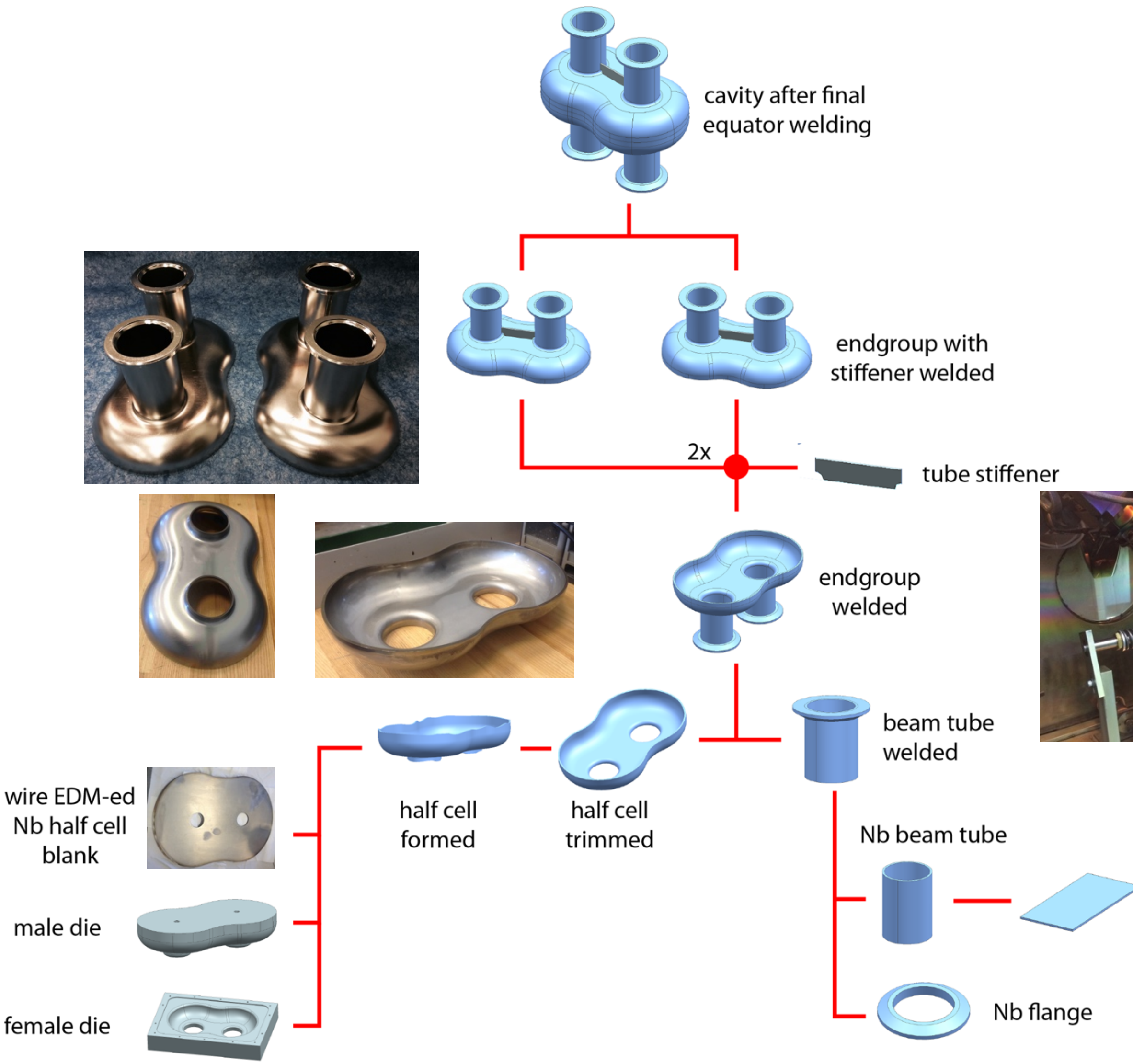


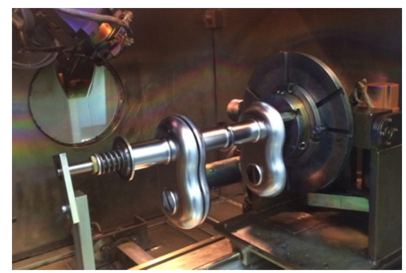


final Nb blank shape (wire EDMed)



Fabrication Flow Chart



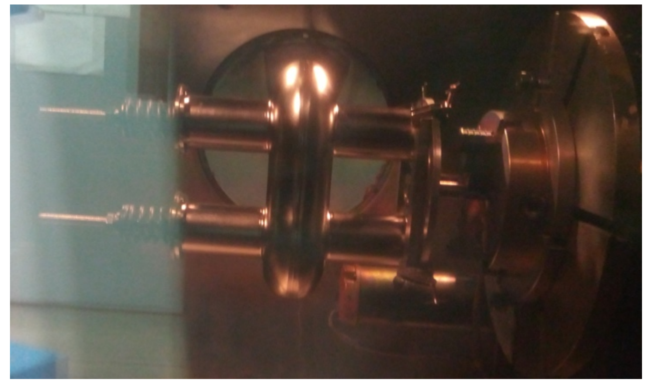


1st prototype twin-axis cavity made from high RRR Nb (cavity #1)

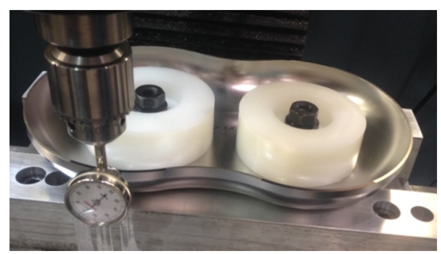
Mechanical Fabrication Completed

- We actually have built 2 prototype cavities concurrently
- One concern was that electron beam welding (EBW) requires full penetration weld along a rather complex curvature with varying beam current

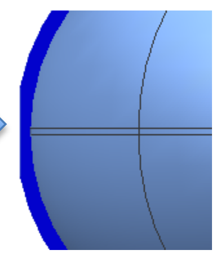
Cavity #1 Cavity #2



cavity in EBW chamber



outside machining on half cells for full penetration weld



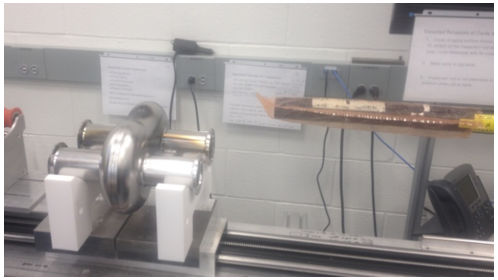
equator weld prep

EBW Experience – 1st Prototype

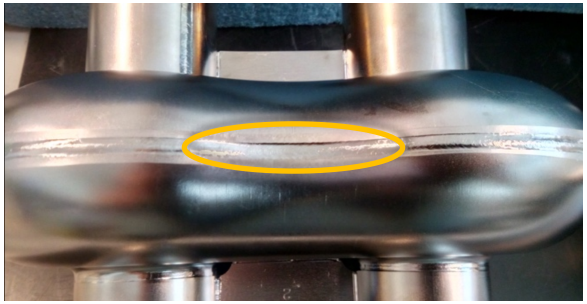
- Outside machining of equator done based on ideal cavity contour
- Does not take into account spring-back effect of cell material after forming
- Equator thickness variations along perimeter was actually on the order of ~1 mm
- Welder decided to weld, but faced issues:
  1) Few blow-thru holes → needed to be patched by local re-weld
  2) No full penetration weld achieved on narrow sides after 1st weld pass
  → 2nd weld pass conducted all around perimeter for repair (twice the weld shrinkage)
- Deep patches likely limit performance
  - Attempt will be made to locally grind blemishes with grinding tool
- Centrifugal barrel polishing is an option depending on outcome

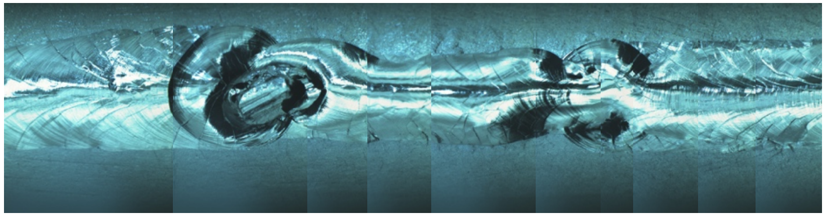
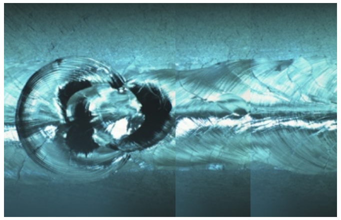

Cell 1: 0.076-0.112” [1.93-2.82 mm]

Cell 2: 0.068-0.108” [1.73-2.74 mm]

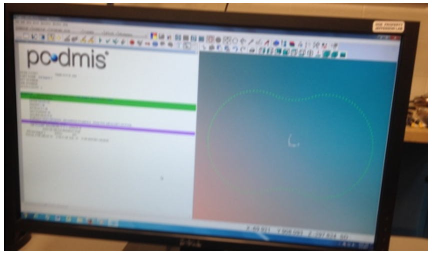
Kyoto camera inspection



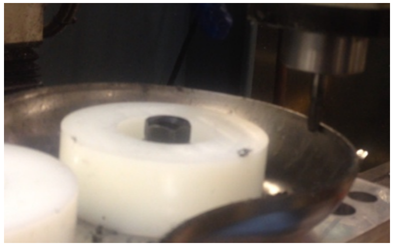



EBW Experience – 2nd Prototype

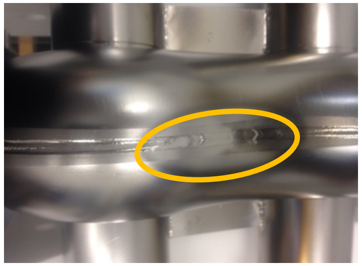
- Lessons learned applied to 2nd prototype
- Outer contour of half cells as pressed has been recorded with CMM
- Inner contour machined with reference to actual outer profile to provide better uniformity of equator thickness around perimeter (0.07” ± ~0.01”)
- Full penetration weld achieved on 1st pass, overall cleaner weld seam
- However: still few holes blown thru, needed local patches

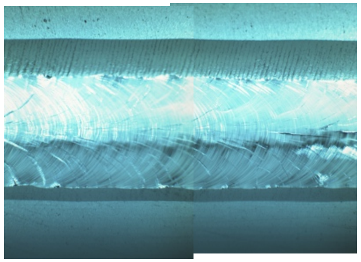


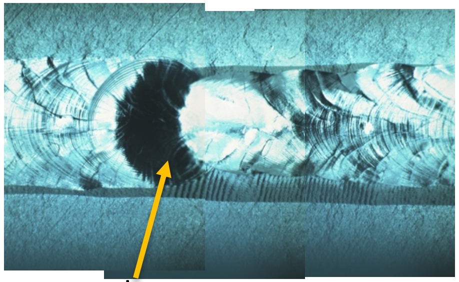
outer cell contour as measured with CMM


Endgroup equators machined at interior to achieve nearly uniform thickness


endgroups after final machining


2nd prototype cavity after equator welding


clean weld seam

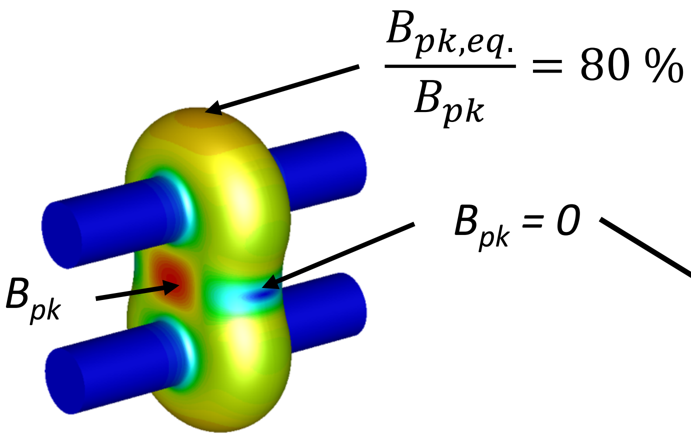

Irregularity, varying e^- (this is not a patch)

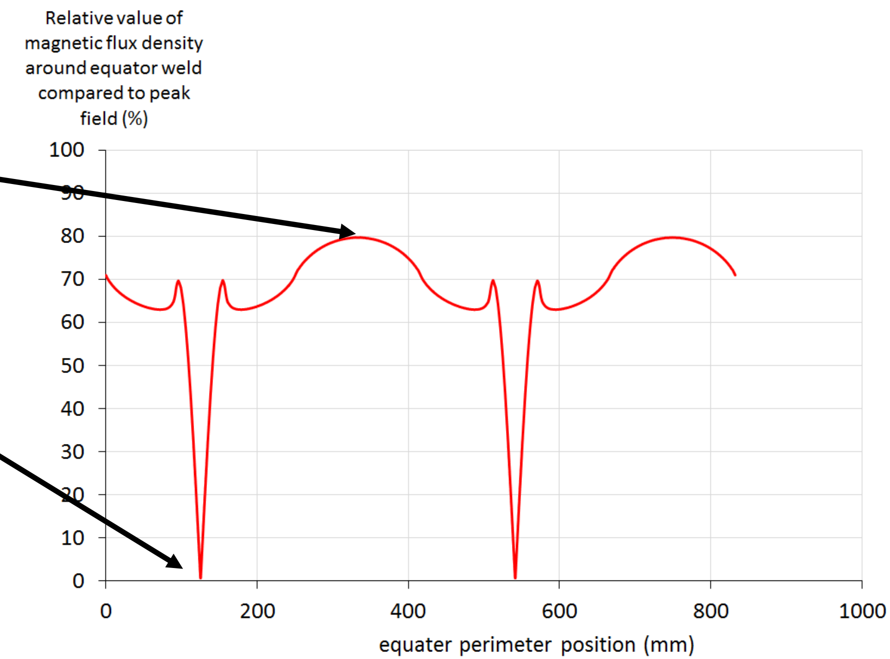
Summary

- Design and fabrication of new twin-axis single-cell cavity completed
- First proof-of-principle, while using standard fabrication techniques
- Actually delivered 2 prototypes (extra cavity beyond scope, but within budget)
- No major feasibility issues concerning production, but several lessons learned as part of prototyping:
  - Equatorial electron beam weld of curved perimeter is not standard, full penetration weld needed (riskier than outside/inside weld)
  - Weld parameter/current changes, JLab welding machine is mature and programming did not allow to vary parameters smoothly, but stepwise
  - Few holes were blown thru and needed local re-welding
  - Equatorial weld preparation improved for 2nd prototype by proper machining based on measured contour after forming → full penetration achieved without 2nd weld pass, overall improved quality of weld seam
  - Welding issues likely avoidable if more time would have been available for practicing welds

Summary

- One design benefit:





- So what's next?
  - Cavity #1 interior will be grinded, CBP considered
  - But cavity #2 will proceed to vertical RF baseline test as-is in parallel
- Chemical post-processing (bulk BCP) is panned for cavity #2
  - High pressure rinse hardware under development
- <u>Vertical test coming soon (all still within budget)…</u>

In Memory of My Beloved Brother

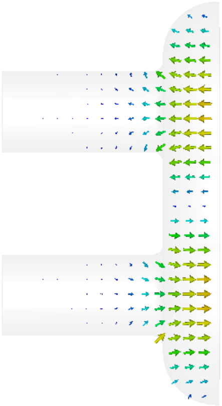
Jost Marhauser

24. Aug. 1973 – 23. July 2016

Back-Up Slides and Additions

Target Frequency

- Target frequency is 1497 MHz at 2K under vacuum, but exact frequency not important for vertical testing (large RF bandwidth)
- For this reason we did not trim half cell equators based on frequency measurements (would need dedicated RF fixture), but aimed for nominal length (incl. weld shrinkage)
- Unfortunately, all (4) endgroups were inadvertently trimmed considerably too short
- Based on length shortage, the expected frequency (warm, air) is 1499.64 MHz
  - Cavity #1 measured: 1506.03 MHz
  - Cavity #2 measured: 1501.27 MHz
  - Discrepancy is Δf = 4.73 MHz, double weld-shrinkage for cavity #2 only accounts for 1 MHz
  - Rest are fabrication tolerances, note: spring-back effect can be large (several MHz)



TM110 trimming sensitivity for endgroup is 4.16 MHz/mm

Mechanical Stiffening of Cavity

- Heat treatment for H2-degassing (typically at 800 °C) reduces Young's modulus (YM) of high RRR Nb material (100 GPa to ~30 GPa)
  - Chemical vapor-deposition of Nb3Sn considered at later stage (T = 1200°C)
  - Need to consider worst case when YM ~ 30 GPa and yield strength ~ 30 MPa
- Beam tubes deflect when cavity evacuated
  - Added minimal stiffening between tubes to stay within the elastic range

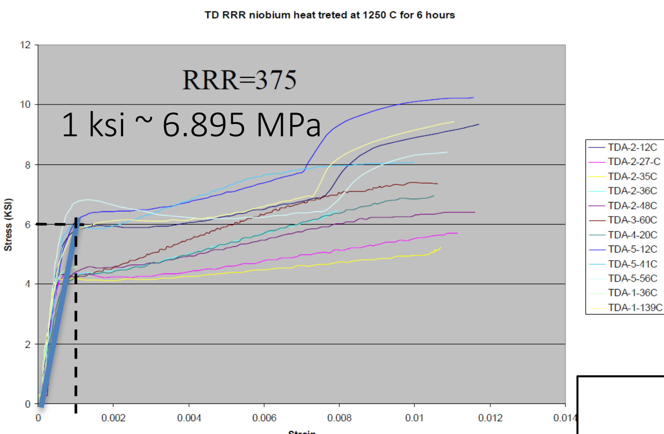
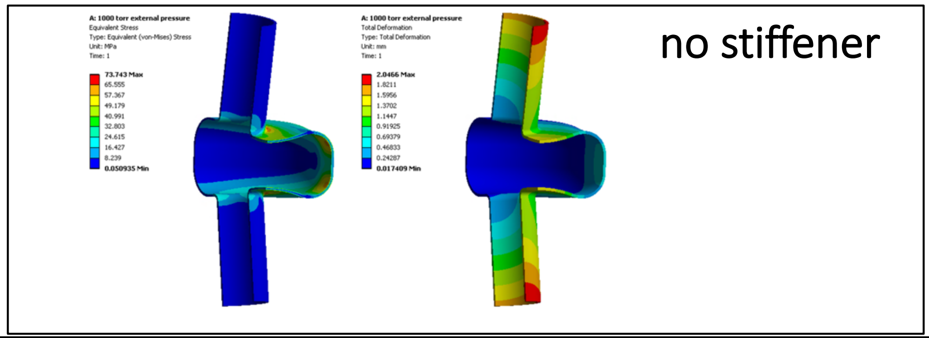


Table I - Summary of the high RRR niobium mechanical properties.
Tableau I - Propriétés mécaniques du niobium de RRR élevé.

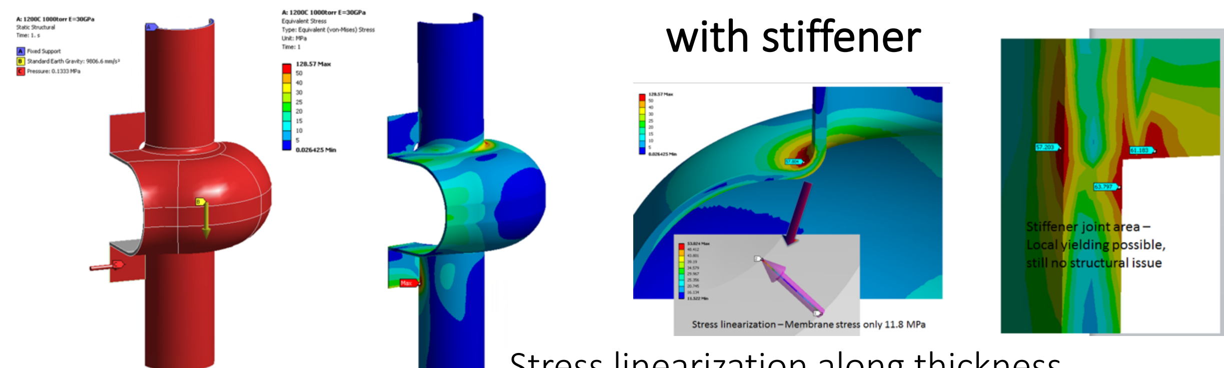
Niobium	Yield Strength (MPa)		Tensile Strength (MPa)		Elongation %		H_v	RRR
	SSR	FSR	SSR	FSR	SSR	FSR		
ASR	51.0	54.5	145	166	44	48	52	260
600°C	48.3	51.7	145	152	48	49	47	300
800°C	39.3	—	131	—	47	—	43	350
1250°C	31.0	43.4	103	131	32	33	36	375

SSR = Slow Strain Rate is 5.561e-5 s^{-1}
FSR = Fast Strain Rate is 2e-4 s^{-1} up to yield point and 1e-3 s^{-1} until break

G.R. Myneni et al., Proc. of SRF 2003



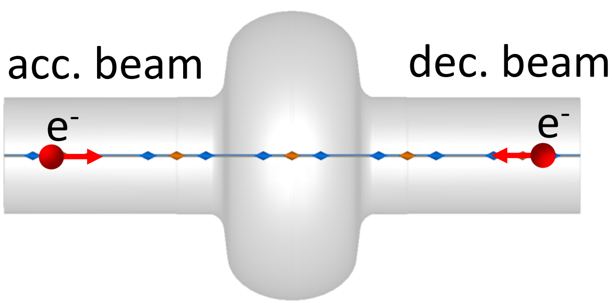
VTA setup with gravity and outside pressure of 0.133 MPa considered



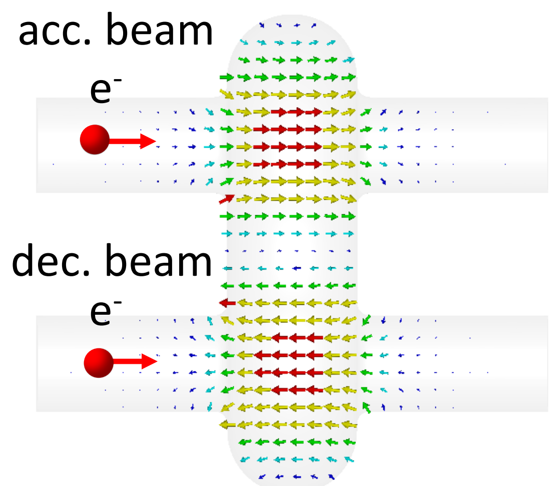
Stress linearization along thickness (Membrane stress) resulted in only 11.8 MPa

2-Beam Excitation Scheme

- Drawback: In twin-axis cavity monopole modes may have dipole components to kick the beam away from tube axis and transverse HOMs can be excited on tube axis since long. field components may exist
- How to quantify drawback without specific ERL design and optics?
- Beam excitation can be resembled numerically with 2-beam excitation scheme to calculate broadband coupling impedance or loss factor
  - Accelerating and decelerating beam in cavity cell at the same time



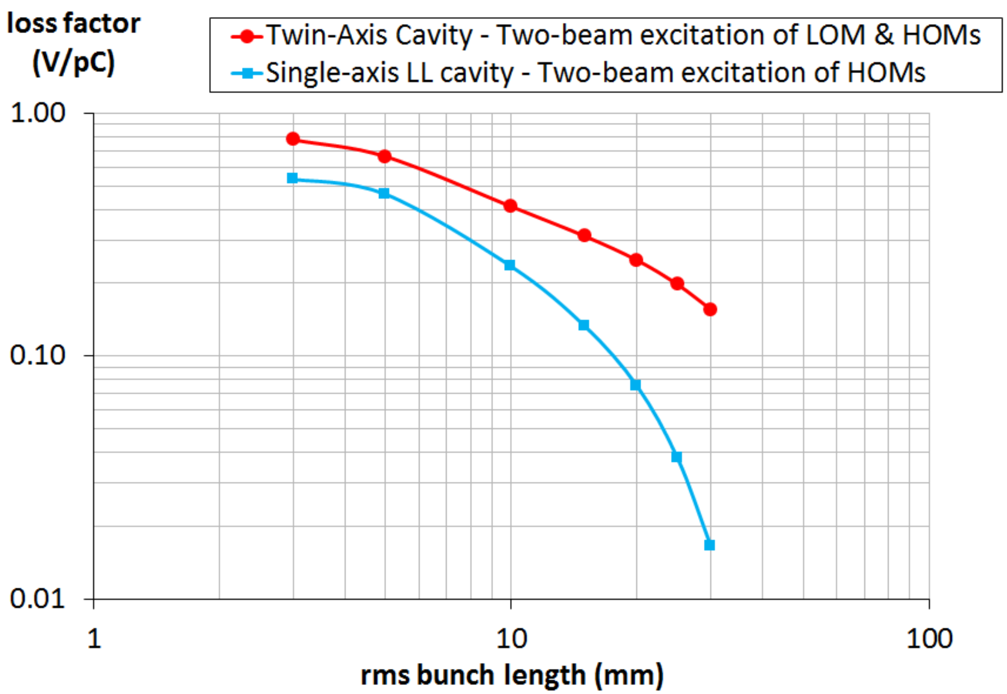
Conventional TM010 cavity
- 2 beams counter-propagating (ERL mode)



Twin-axis TM110 cavity
- 2 beams co-moving (ERL mode)

2-Beam Loss Factor

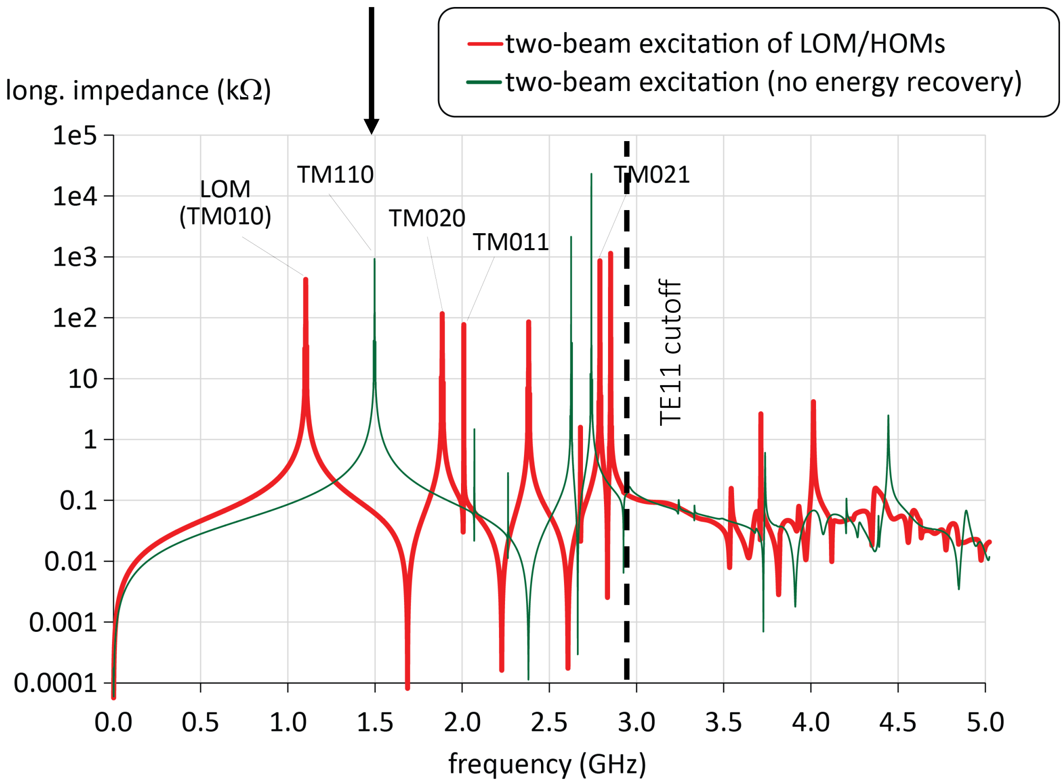
- Expect larger energy deposition in parasitic modes for twin-axis cavity compared to standard single-axis cavity
- Machine and beam-pattern dependent BBU impedance instability threshold must be considered
- Avoid beam spectral lines by design
- HOM-damping necessary

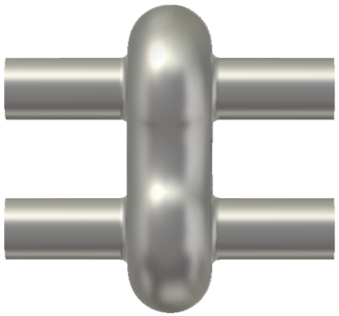


2-Beam Coupling Impedance

- Unresolved (bare cavity) broadband coupling impedance on tube axes

Operating mode - zero beam loading

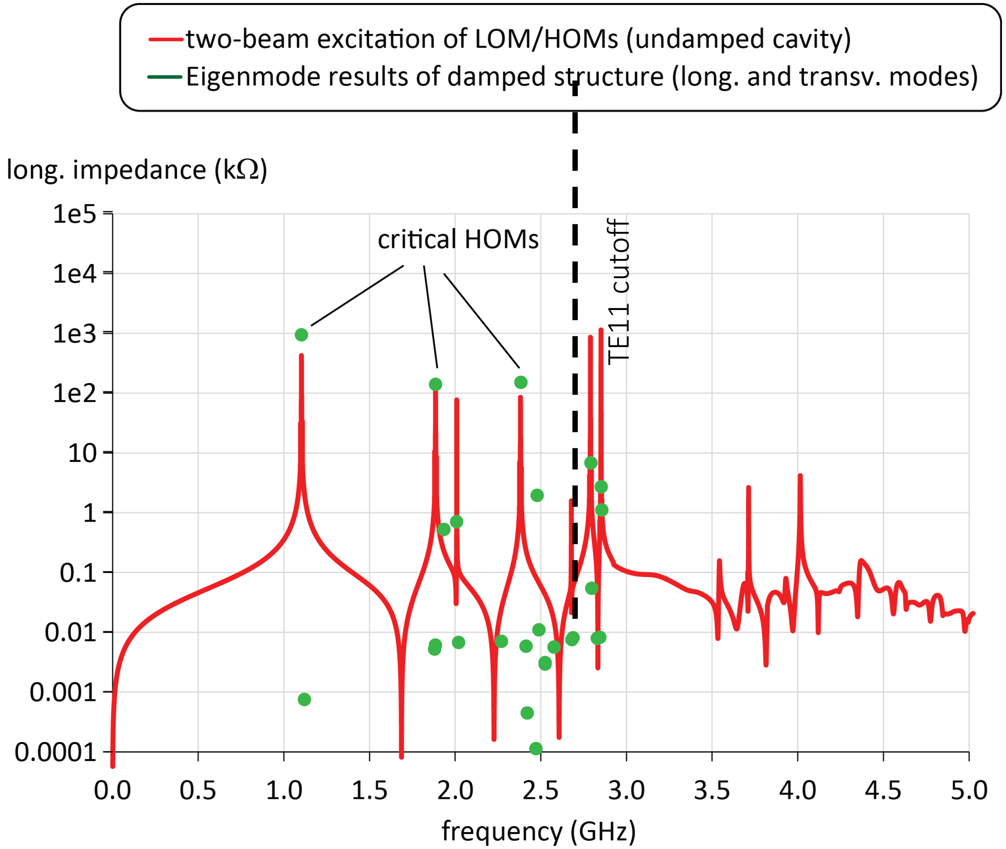


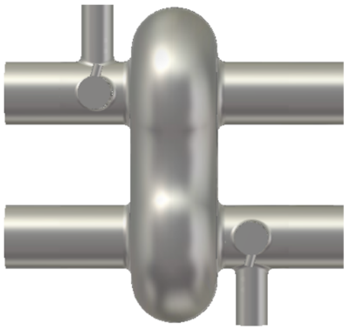


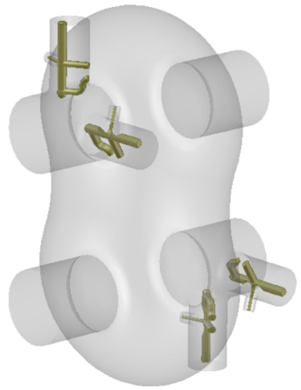
Bare cavity

2-Beam Coupling Impedance

- Preliminary study – add HOM couplers (beyond scope funded project)
- TESLA-type coaxial couplers (scaled), no further optimization
- Critical HOM impedance can be damped further with adequate coupler design – up to 4 beam tubes available



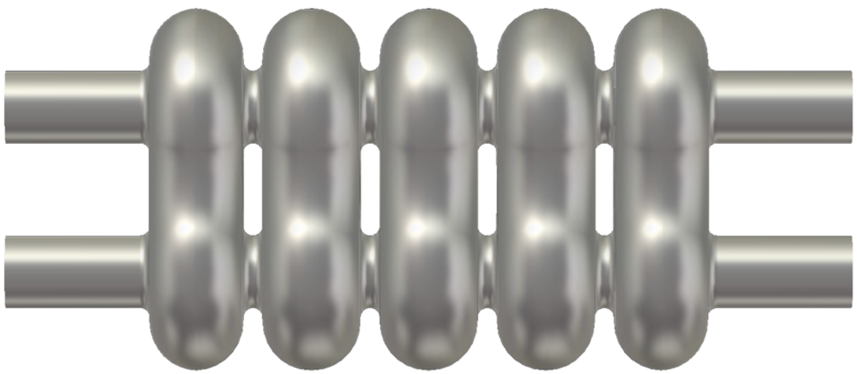


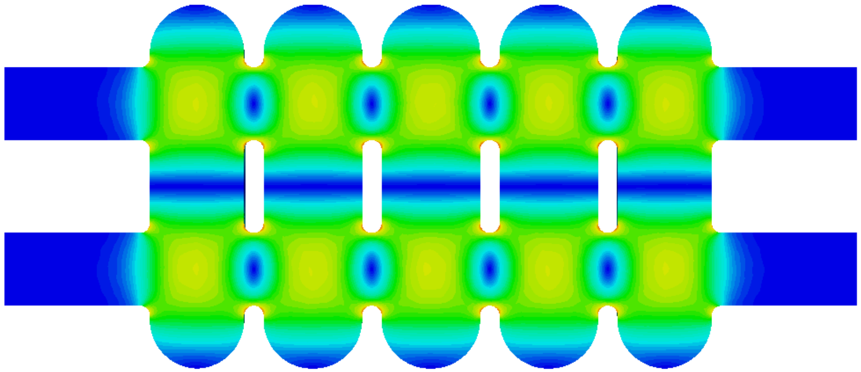


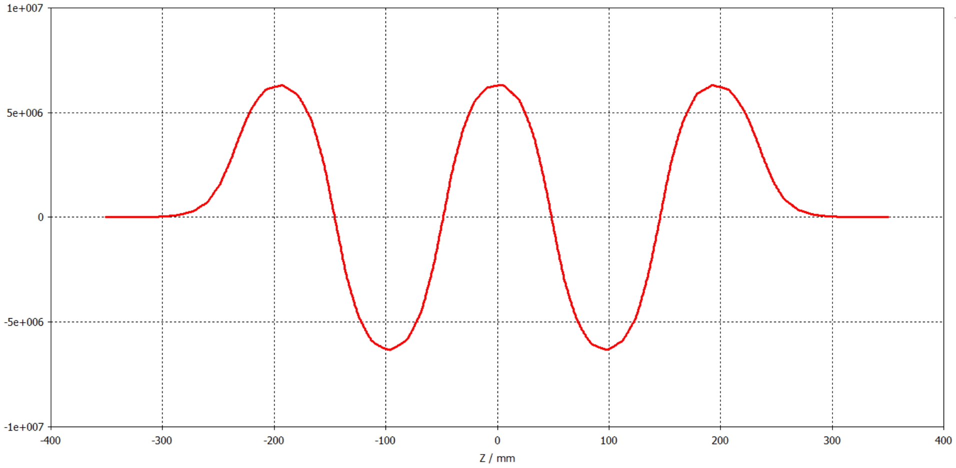
TESLA-type coaxial couplers (scaled – no optimization)

Prospect for Multi-Cell

- Single-die design built in consideration of fabrication of a multi-cell cavity
- HOM-damping studies beyond scope of funded project





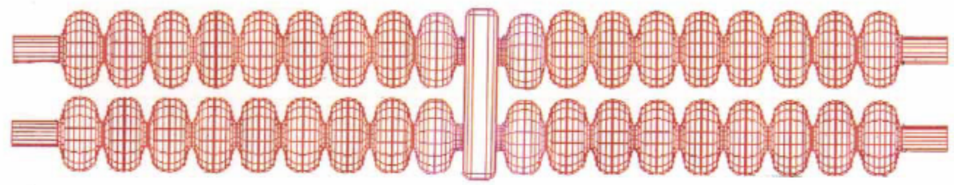


Alternative

- Two independent cavities, one resonant coupling cell for TM010 operational mode (only)

MULTI-BEAM ACCELERATING STRUCTURES

Shuichi Noguchi† and Eiji Kako
KEK, High Energy Accelerator Research Organization
1-1 Oho, Tsukuba, Ibaraki, 305-0801, Japan



- Mitigate regenerative BBU with cavities of slightly different shape and decoupled HOMs
  - Threshold current for instabilities increase by factor ~5 compared to symmetric cavities

PHYSICAL REVIEW ACCELERATORS AND BEAMS 19, 083502 (2016)

Asymmetric dual axis energy recovery linac for ultrahigh flux sources of coherent x-ray and THz radiation: Investigations towards its ultimate performance

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[1] *John Adams Institute at University of Oxford, OX1 3RH, Oxford, United Kingdom*
[2] *Cockcroft Institute, Lancaster University, LA1 4YW, Lancaster, United Kingdom*

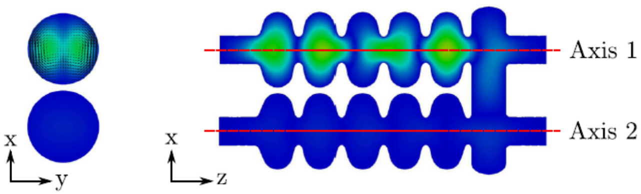

FIG. 10. A transverse and longitudinal slice showing the electric field contour plots for a mode at 1.73 GHz. The transverse slice also shows the magnetic field as indicated by the cones.

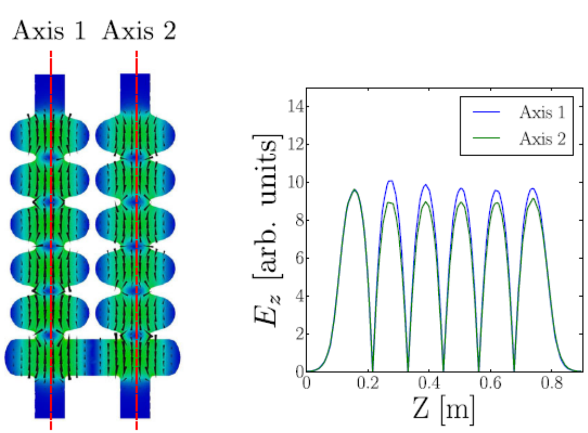

FIG. 8. A contour plot of the electric field distribution for the operating mode (left) and the electric field along each axis (right).