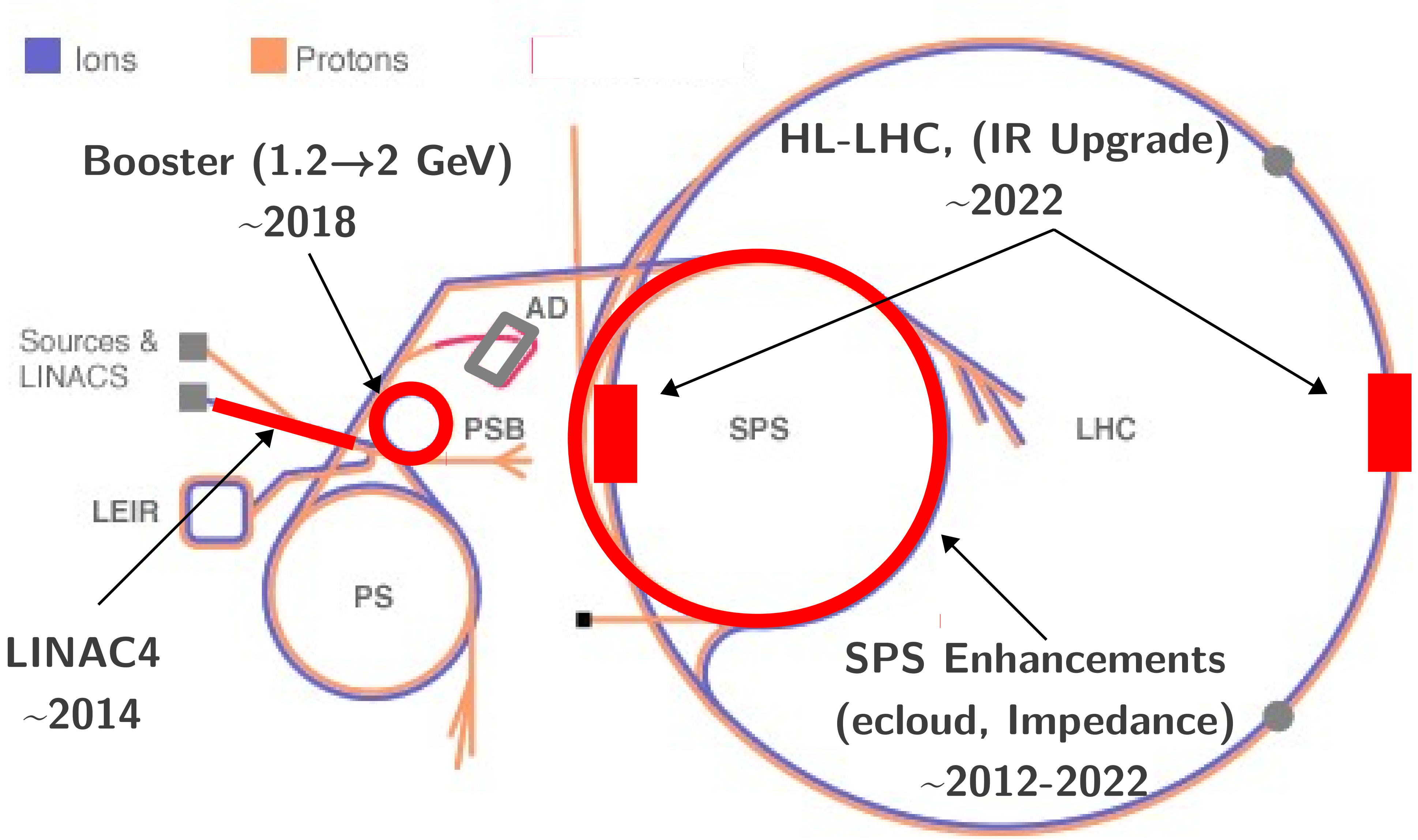
Crab Crossing for LHC

R. Calaga, E. Ciapala, E. Jensen, F. Zimmermann

RFTECH, Dec 12 2011

- LHC upgrade, recap
- Evolution of technology concepts & studies
- Planning & future activities

CERN Accelerator Chain



Booster (1.2→2 GeV)
~2018

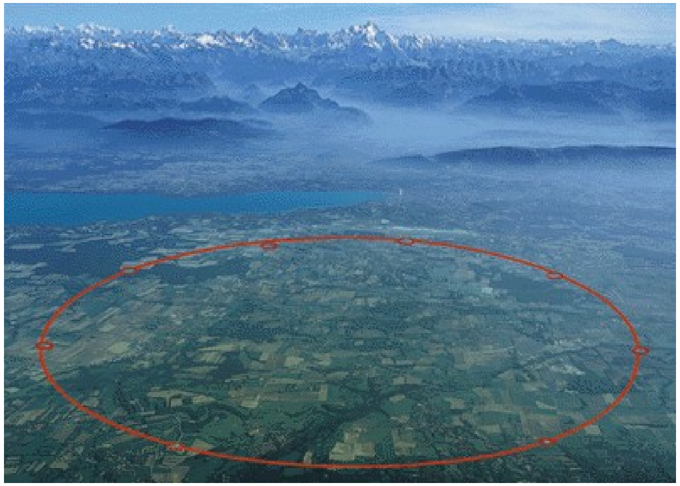
HL-LHC, (IR Upgrade)
~2022

LINAC4
~2014

SPS Enhancements
(ecloud, Impedance)
~2012-2022

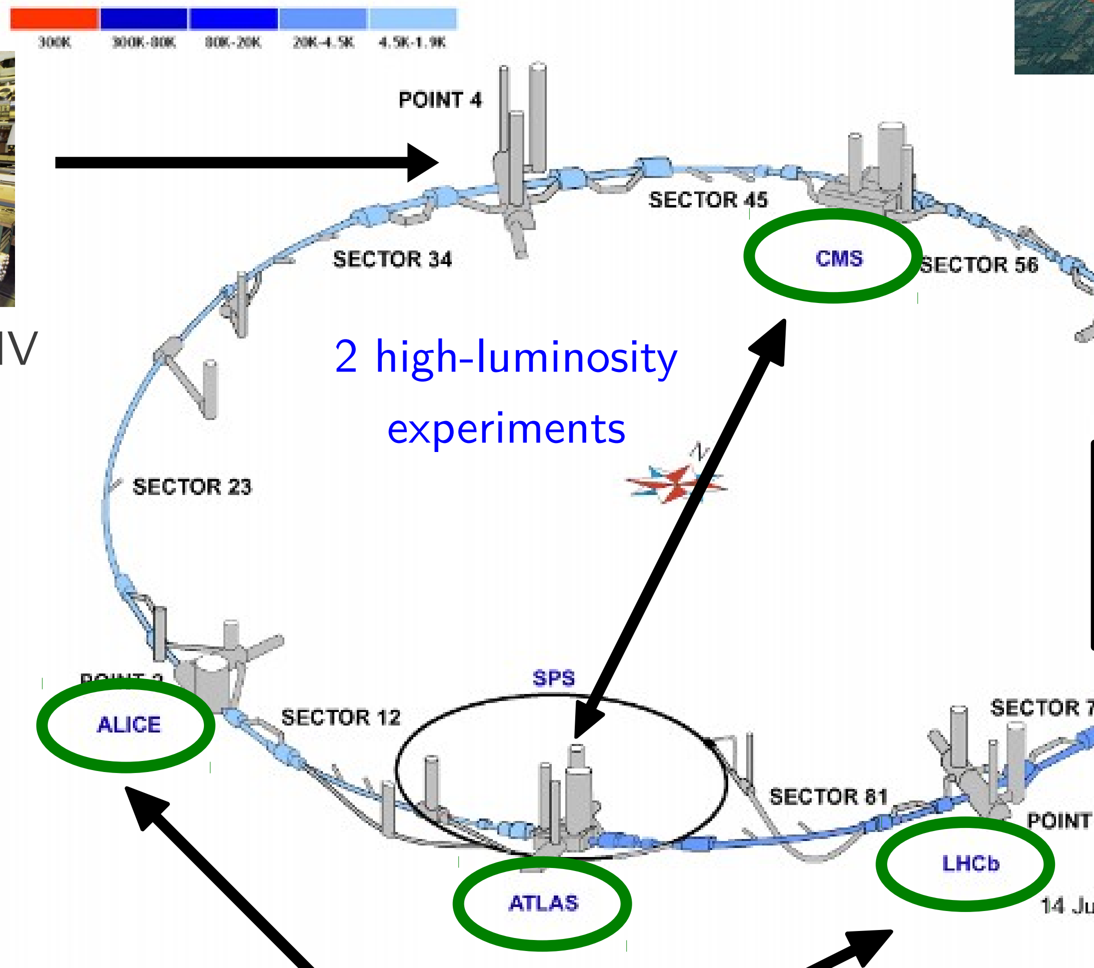
🟥 **Upgrades**

THE LHC



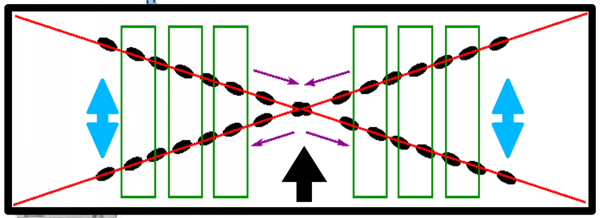
27 km @1.9K to accelerate protons to 7TeV

400 MHz SRF, 16MV



2 high-luminosity experiments

2 experiments to study anti-matter & heavy ions



32 Long-range /IP

LHC: TODAY & FUTURE

2023

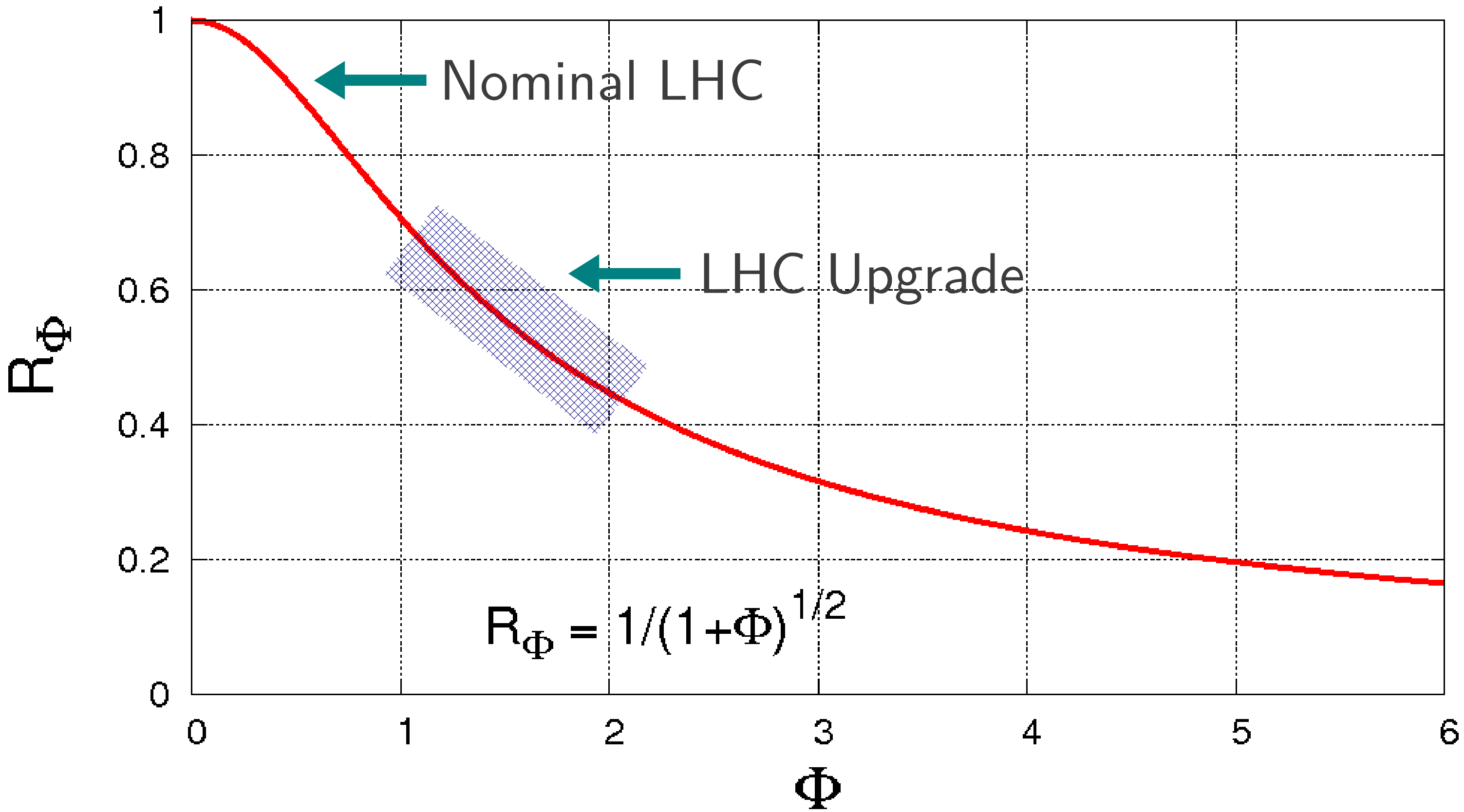
	Today	Design	Upgrade
Energy [TeV]	3.5	7.0	7.0
Intensity [x 10^{11}]	1.1-1.2	1.15	$\geq$ 1.7
N. Emittance (μm)	2.2-2.5	3.75	$\leq$ 3.75
β* (cm)	100	55	15
# of bunches	1380	2808	2808
L_{peak} [x 10^{34}]	0.19	1	~20*
L_{int} [fb^{-1}/yr]	~6	67	250

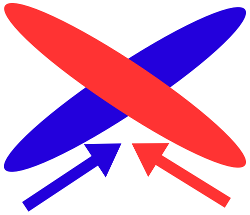
larger x-angle ←

*Luminosity leveling → 5 x 10^{34} [cm^{-1} s^{-1}]

Ultimate goal by 2030: 3000 fb^{-1} (Radiation damage limit ~700 fb^{-1})

X-ANGLE & REDUCTION





Inefficient overlap

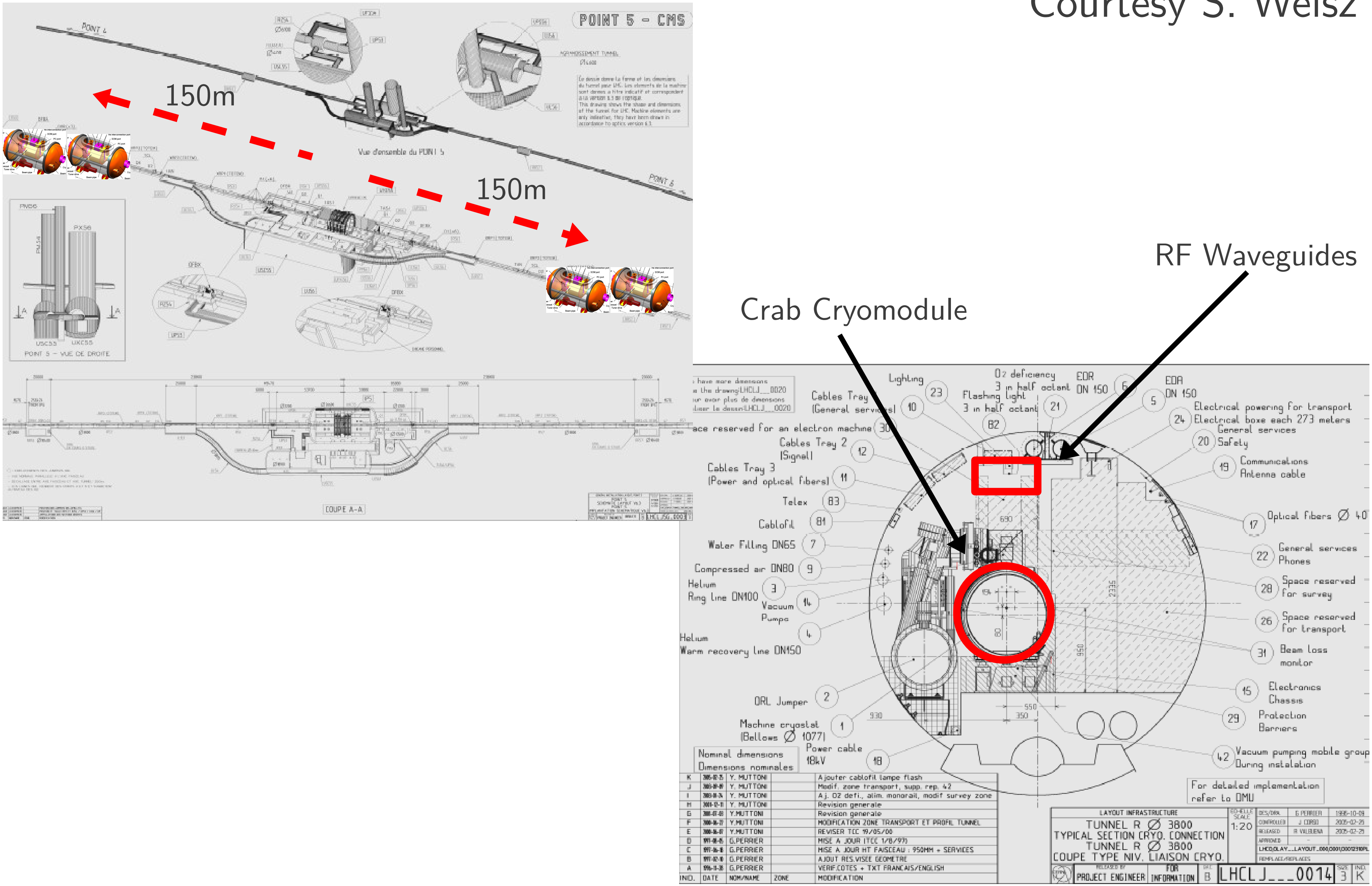
$$\Phi = \frac{\sigma_z \theta_c}{\sigma_x}$$

$$V_{RF} \propto \frac{1}{\sigma_z^4}$$ → Unfavorable voltage scaling

$$V_{CRAB} \propto \theta_c$$ → Effective recovery + lumi leveling

INTERACTION REGION, LHC

Courtesy S. Weisz



RF Waveguides

Crab Cryomodule

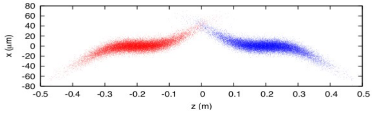
CAVITY SPECIFICATION

RF

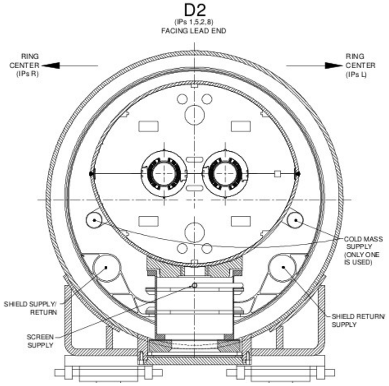
Geometrical

Optics

Baseline	**Unit**	**LHC**
Frequency	MHz	400 (800)
Deflecting Voltage	MV/Cav	3
Peak E-field	MV/m	< 50
Peak B-field	mT	< 100 mT
Aperture (diameter)	mm	84
Cav Outer Envelope	mm	< 150
Module length	m	$\sim$ 1m
HV crossing	-	Desirable
β* (IR1/IR5)	cm	15-25
β crab	km	~ 5
Non-linear harmonics	Units [10^{-4}]	2-3
Impedance Budget/cav	Longitudinal, Transverse	300kΩ, 187kΩ/m

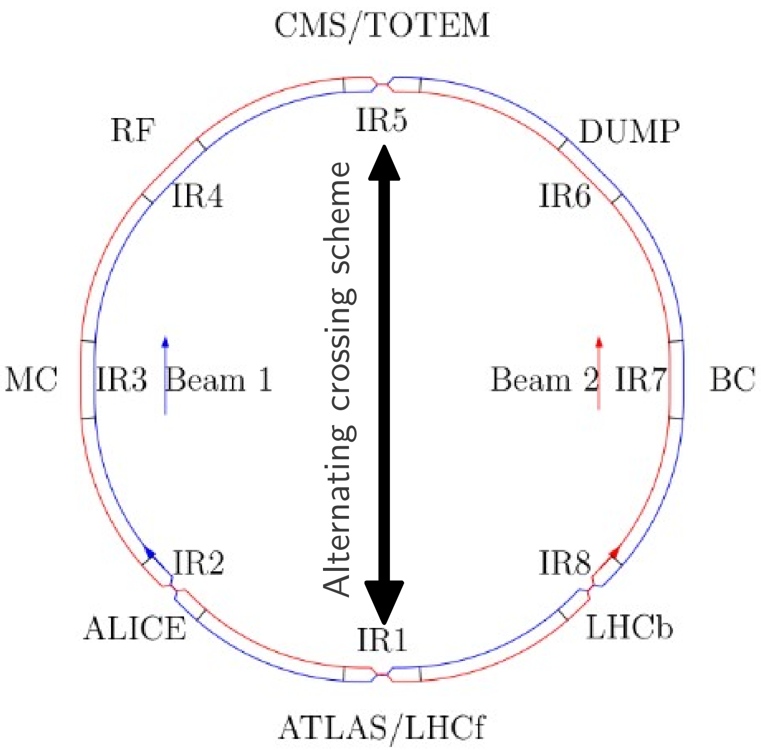


$\sigma_z = 7.55$ cm



Beam-beam separation

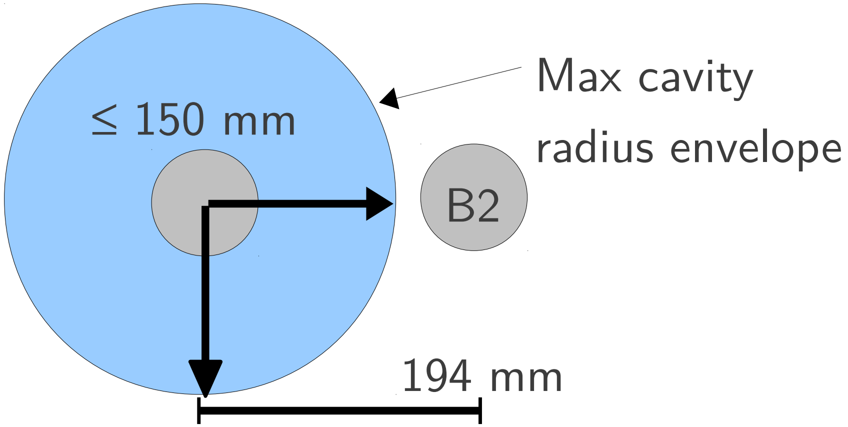
Baseline scheme requires compact size



Frequency: 400 MHz

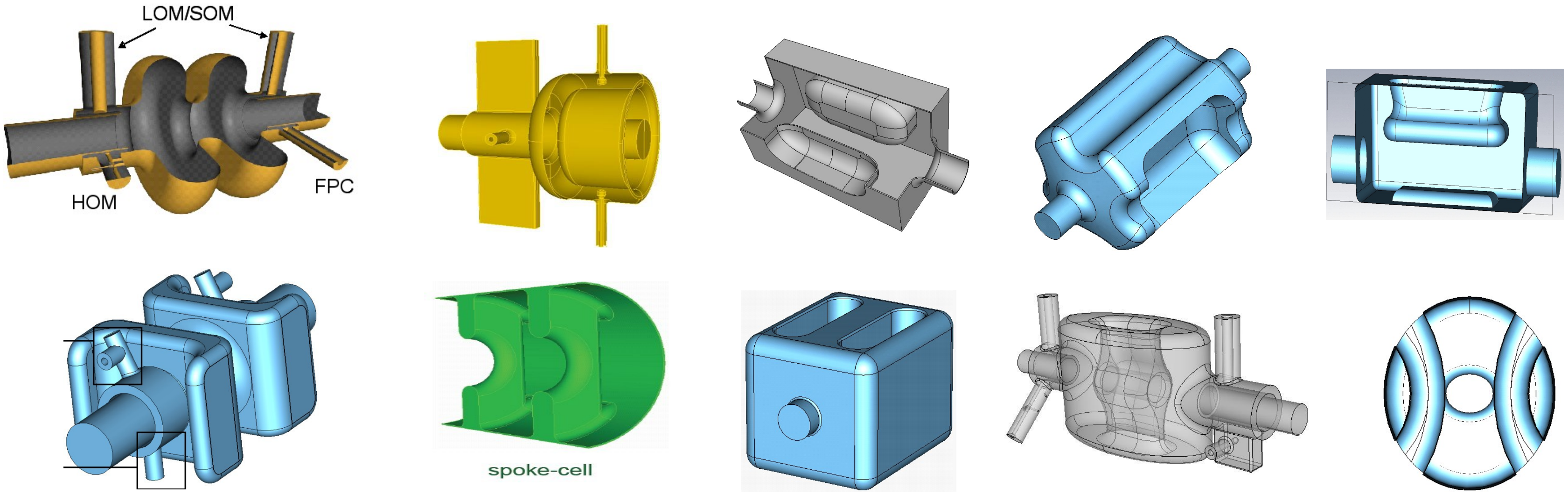
BP radius: 42 mm

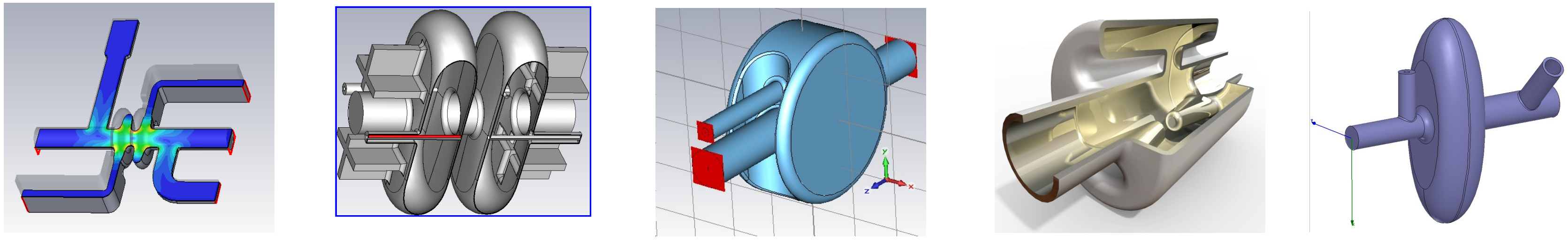
Outer envelope: < 150mm



WORLDWIDE DESIGN EFFORT

~4yr of design evolution

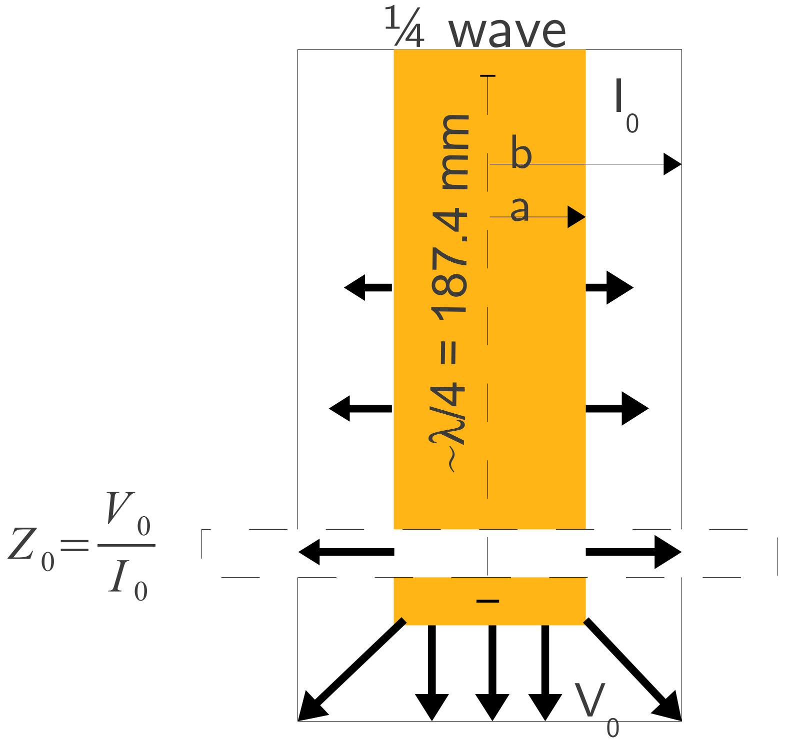




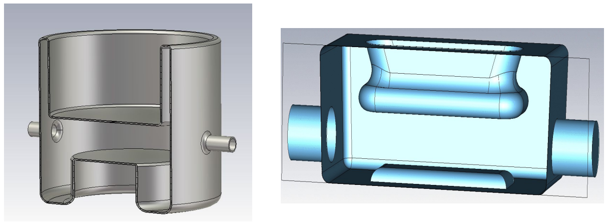
Exciting & rapid development of deflecting cavities

(BNL, CERN, CI-DL-LU, FNAL, KEK, ODU/JLAB, SLAC)

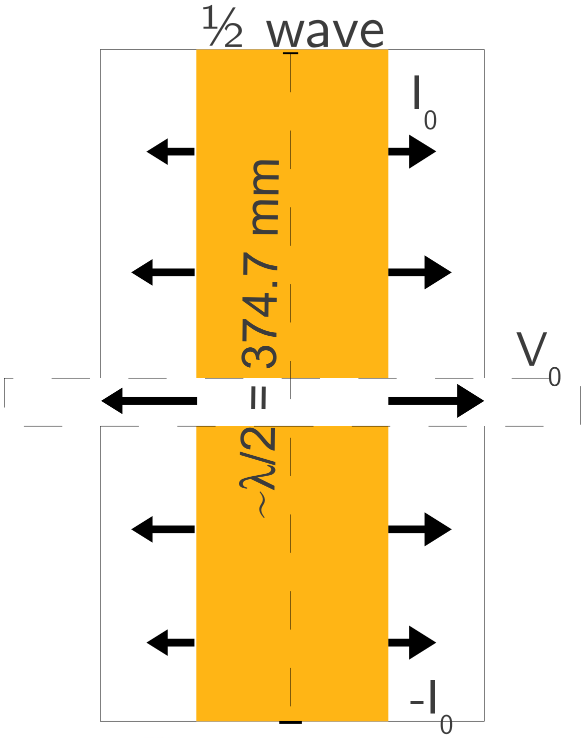
Coaxial Line, Schematic

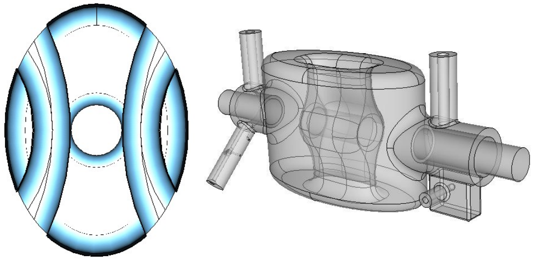


$Z_0 = \frac{V_0}{I_0}$



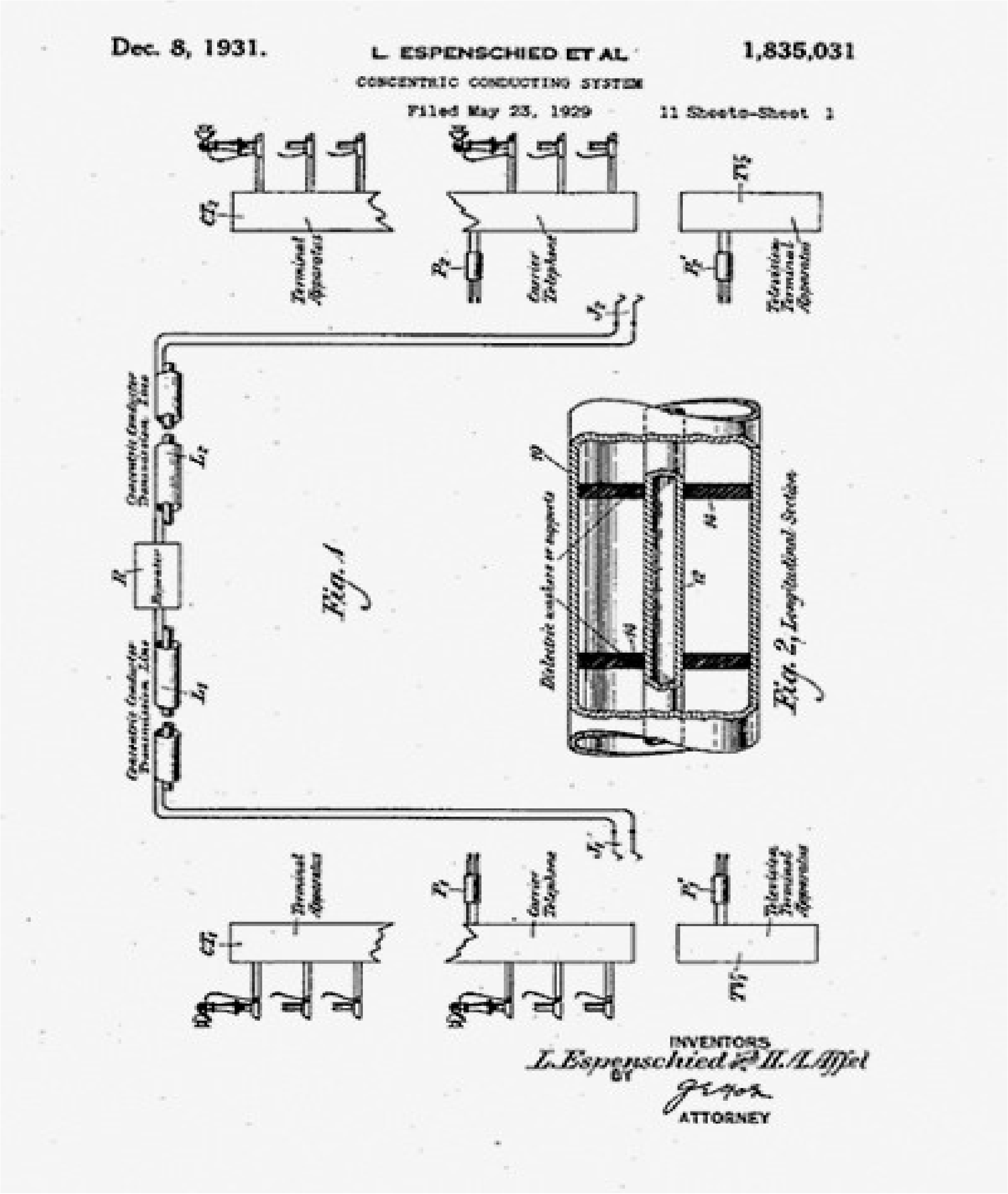
x 2 =





Pillbox cavity → Transversely ~λ (x4 bigger)

Coaxial Cable Patented, 1931

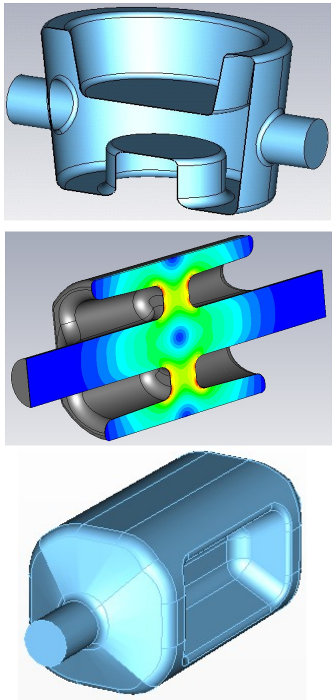


Dec. 8, 1931. L. ESPENSCHIED ET AL 1,835,031

CONCENTRIC CONDUCTING SYSTEM

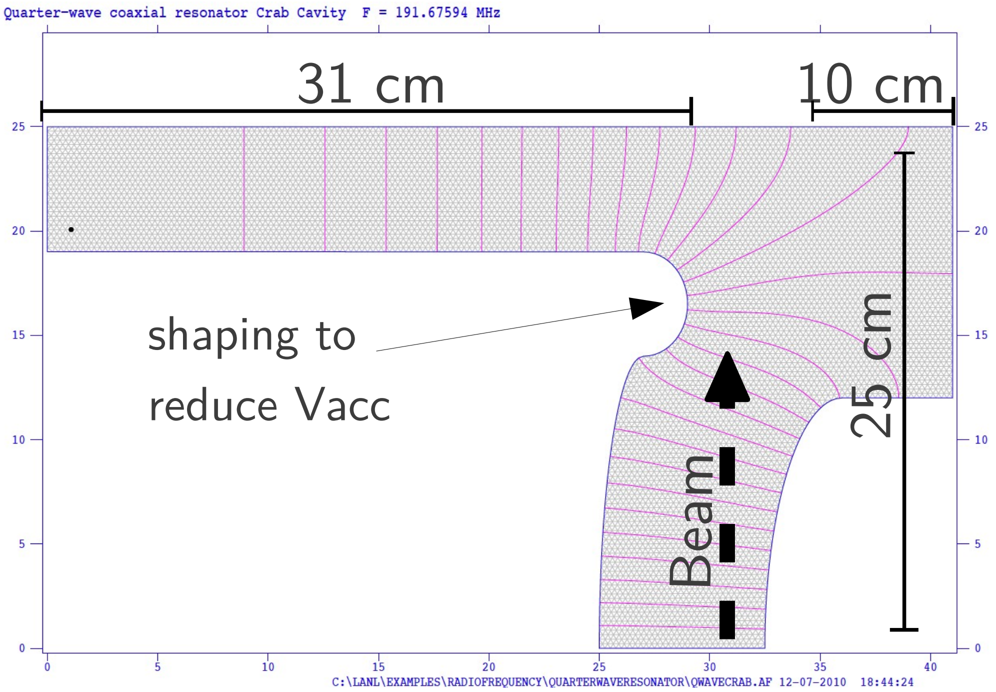
Filed May 23, 1929 11 Sheets-Sheet 1

80 yrs later

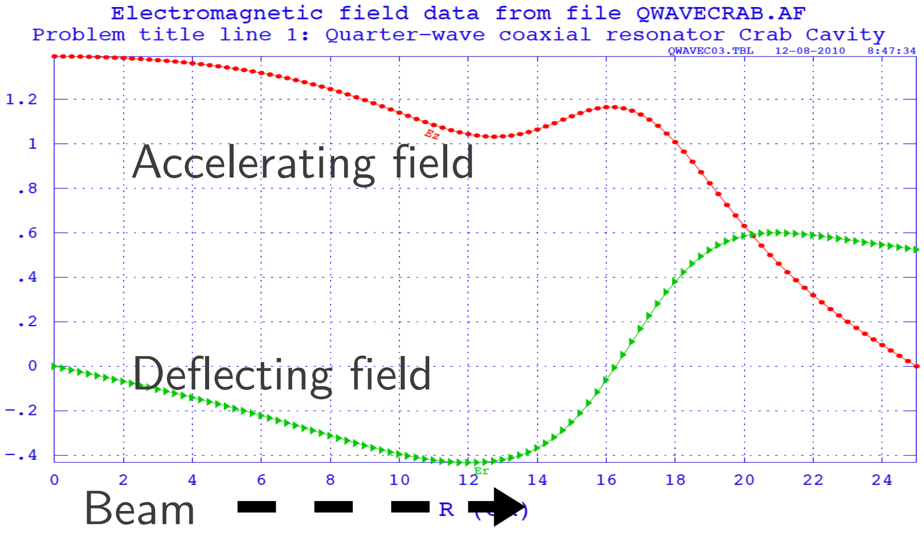


First Proposal

LHC-CC10



Frequency	192 MHz
Next Mode	411 MHz
Tran. Volt	5.0 MV
Epk	29 MV/m
Bpk	62 mT
Eacc	0.47 MV

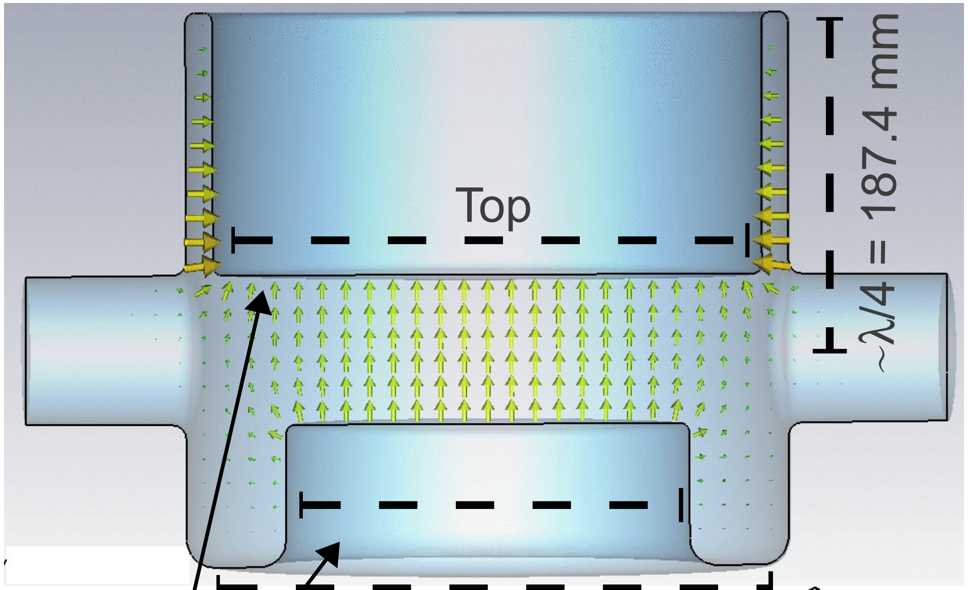


Single TEM-class cavity

HOMs separated by about x3

Non-zero V_{acc} ~10%

Suppression of V_{ACC}

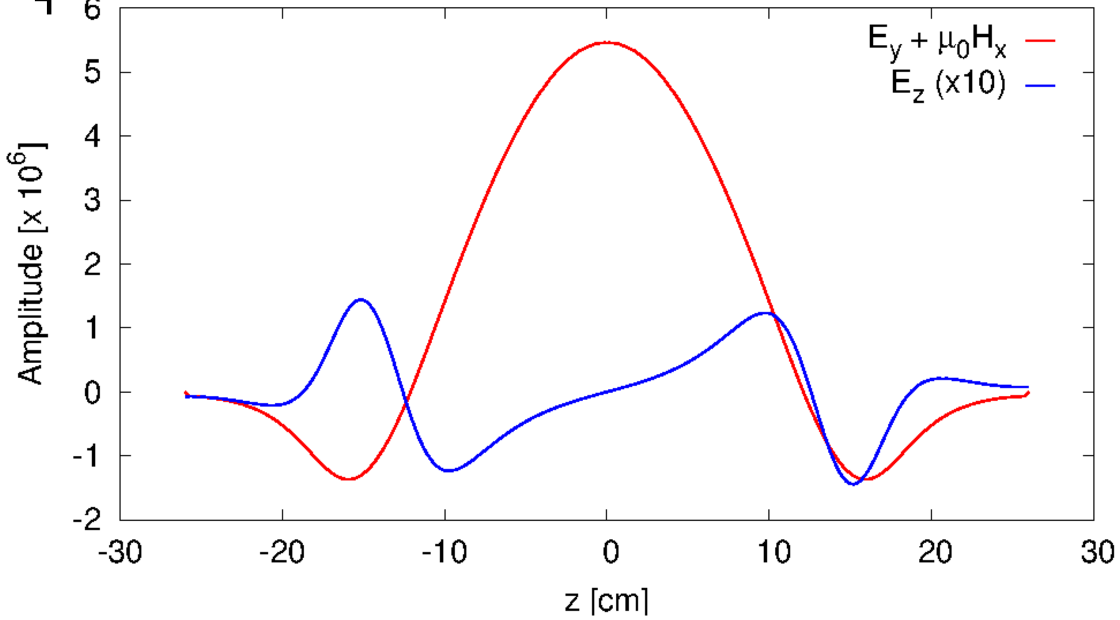


Resort back to simple ¼ wave

Adjust the top/bottom

conductors & lengths/heights

For suppression

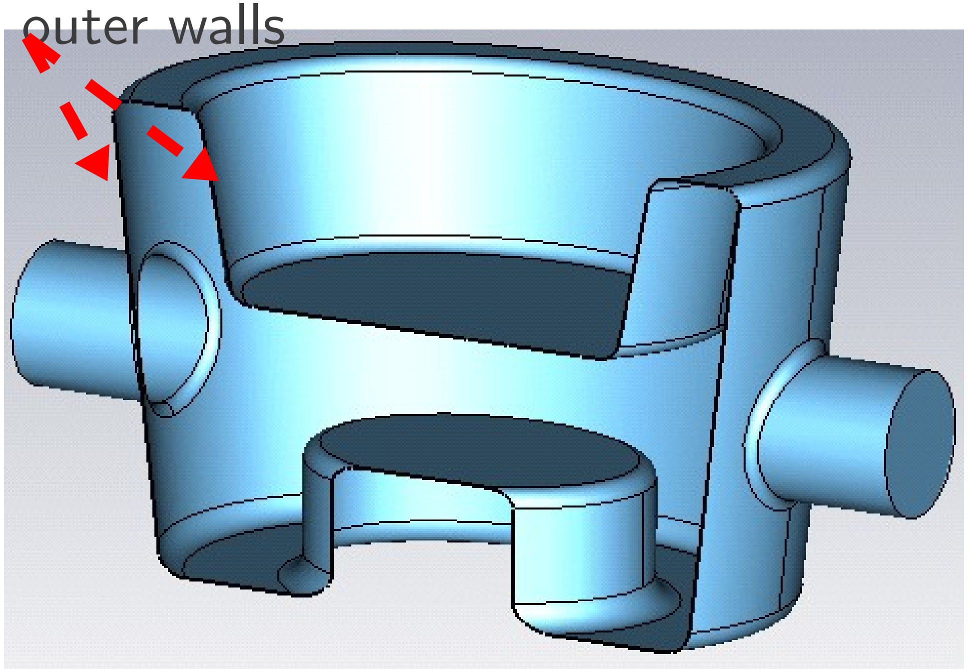


OPTIMIZATION, FOR EXAMPLE

Differential tapering (~10-15^0)

of the inner & outer walls

$V_{\perp}$	2.5 MV
R/Q⊥	318 Ω
Epk	39 MV/m
Bpk	59 mT
Vacc	120 kV (4.8%)



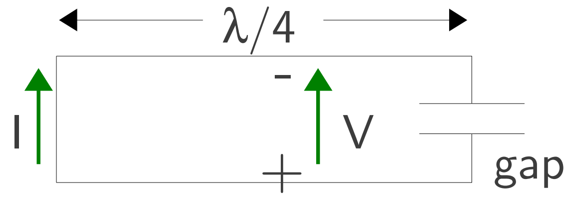
Balance carefully peak surface fields vs. Vacc

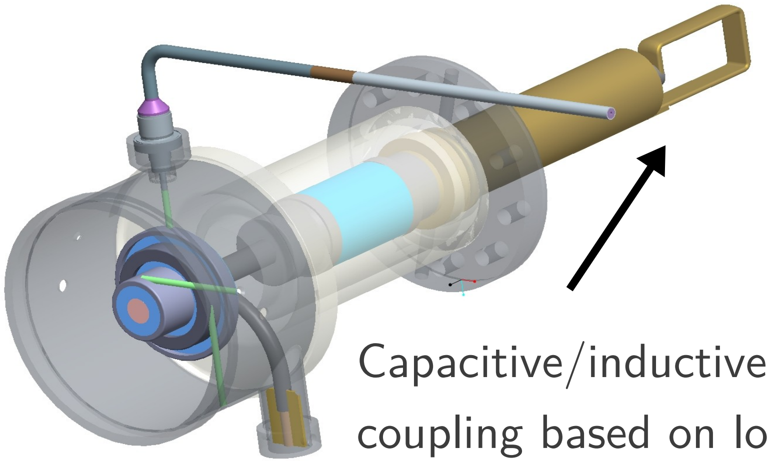
Multipacting suppression by geometry modifications

HOM COUPLER

For pure ¼ wave: $Z_0 \tan(\beta l) = \dfrac{1}{\omega C_{gap}}$

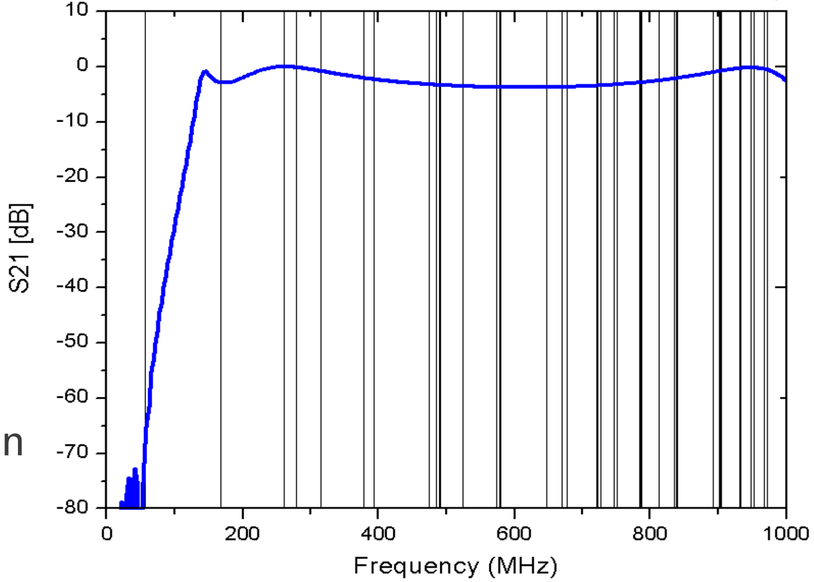
HOMs approx → $\beta l = n\pi$





Capacitive/inductive coupling based on location

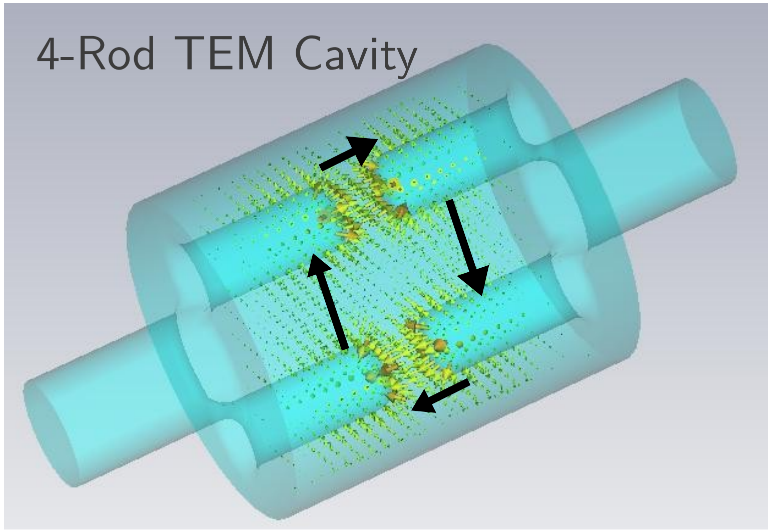
Example coupler for 56 MHz Cavity



- High-pass filter design (simple & robust)
- HOM & damping analysis underway

LU-DI (JLAB) Design

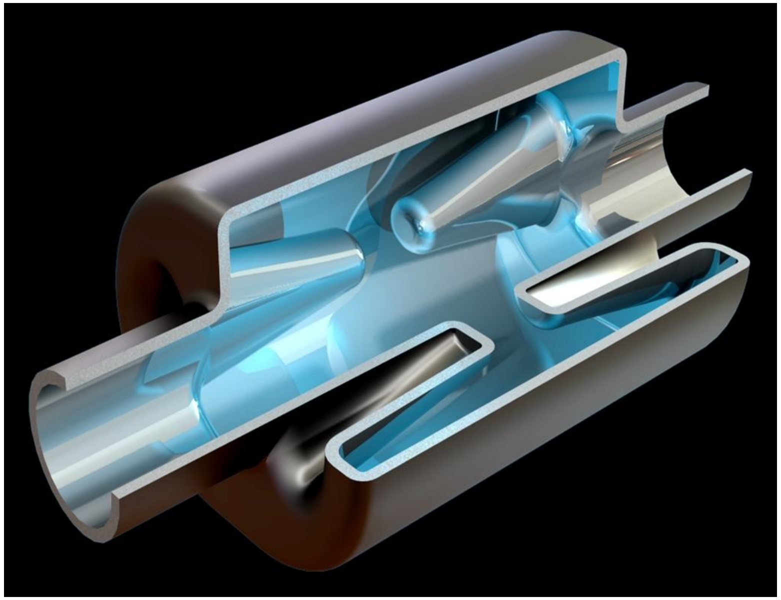
Courtesy G. Burt, B. Hall



4-Rod TEM Cavity

Towards

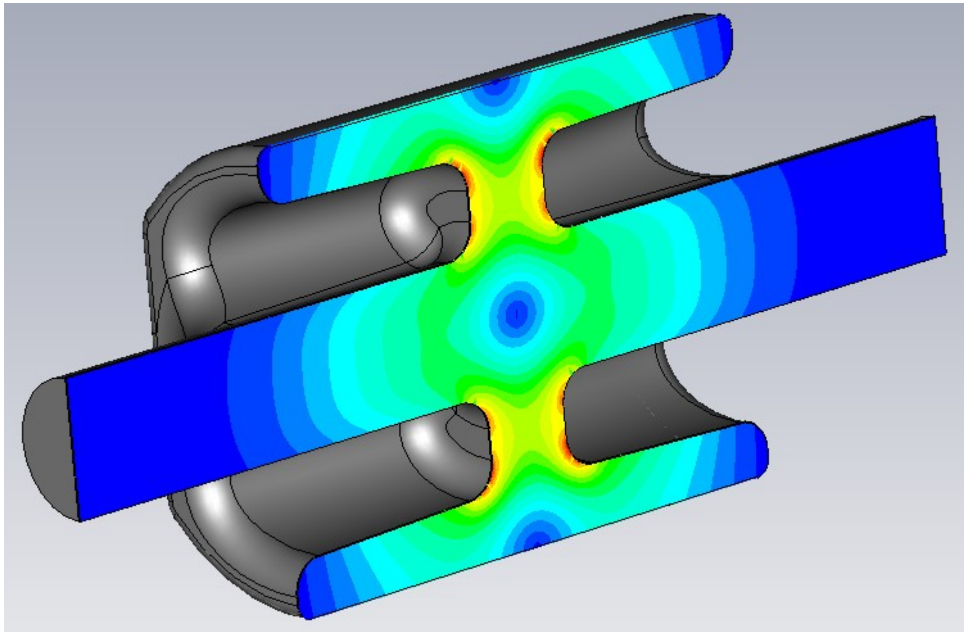
Conical rods



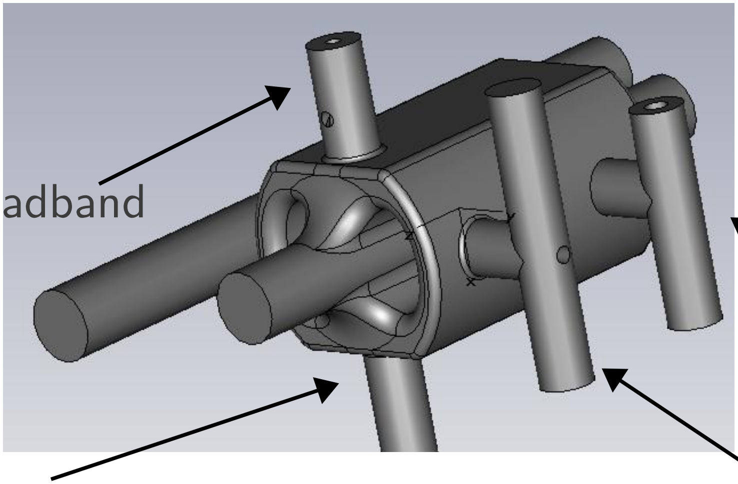
- Four λ/4 resonators to form RF deflectors
- NC version operating already used at JLAB
- Lower order modes exist

4R Design, LU-DI

Courtesy G. Burt, B. Hall



Freq	400 MHz
Vt	3 MV
Epk	39.2 MV/m
Bpk	59.1 mT
R/Q	953 Ω µ



HOM Broadband

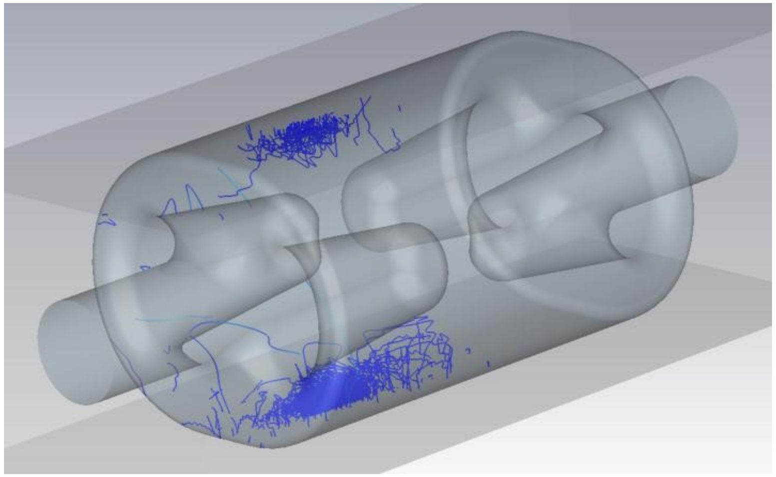
Input Coupler

HOM Probe Coupler

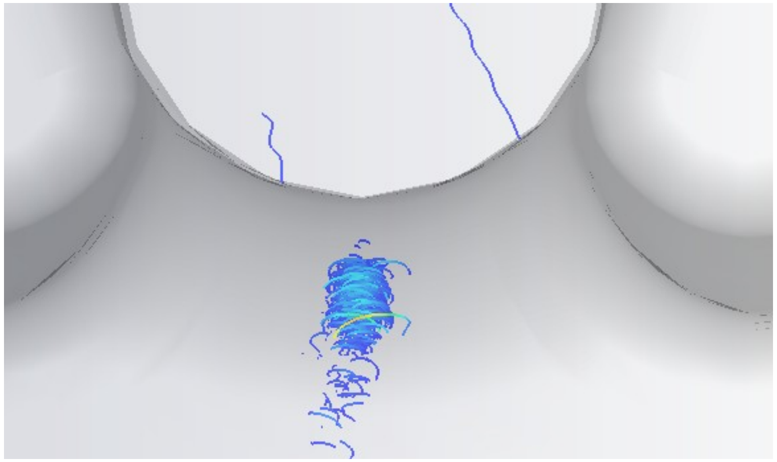
LOM Coupler

4R Multipacting

Courtesy G. Burt, B. Hall



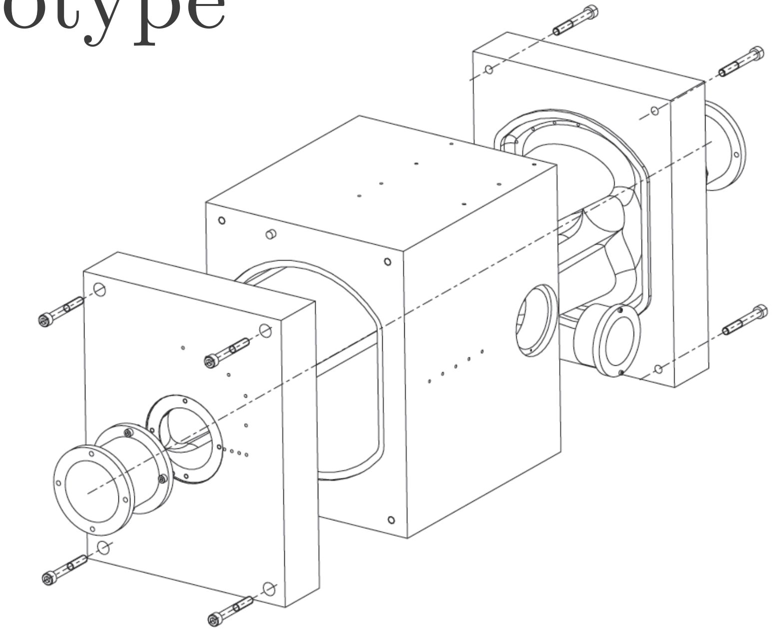
Weak multipacting observed at the Rods, 0.15 MV



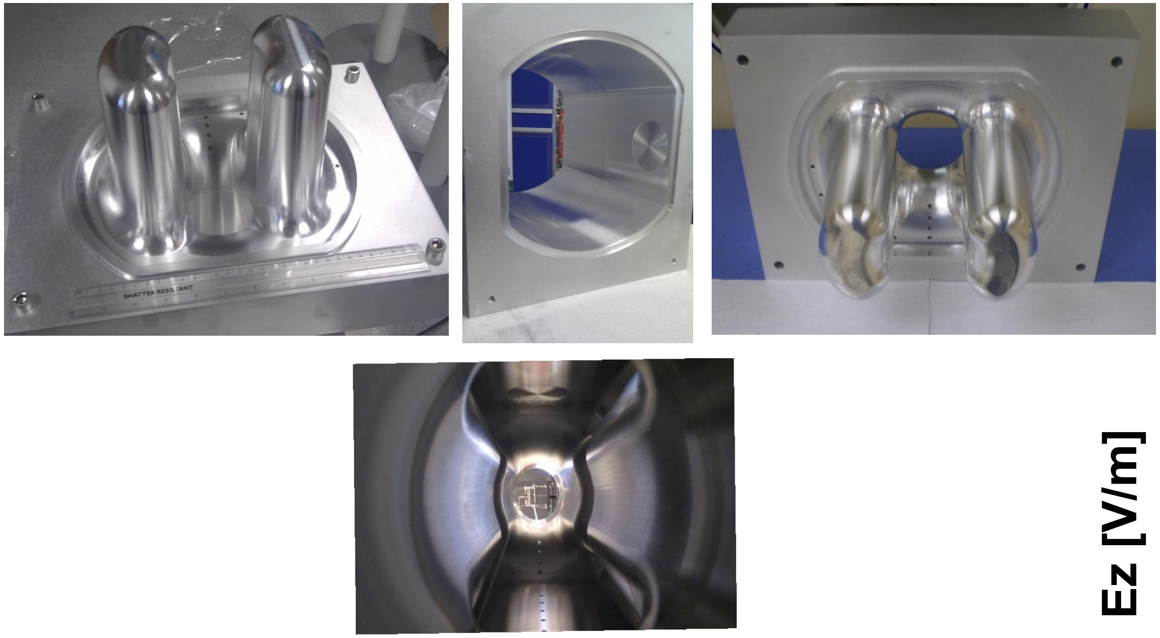
Strong multipacting observed at the beam pipe, 1.6 MV (similar to KEKB cavities)

4R Al-Prototype

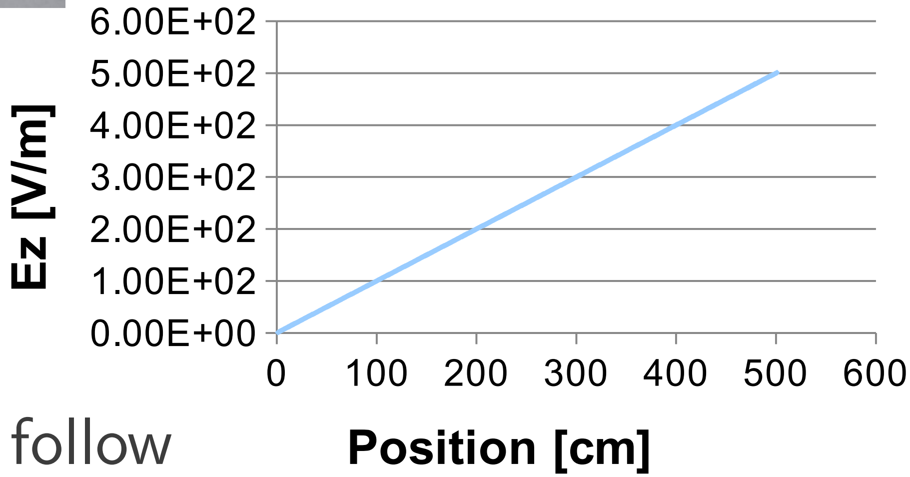
Courtesy G. Burt, B. Hall



Nb Cavity from solid Ingot



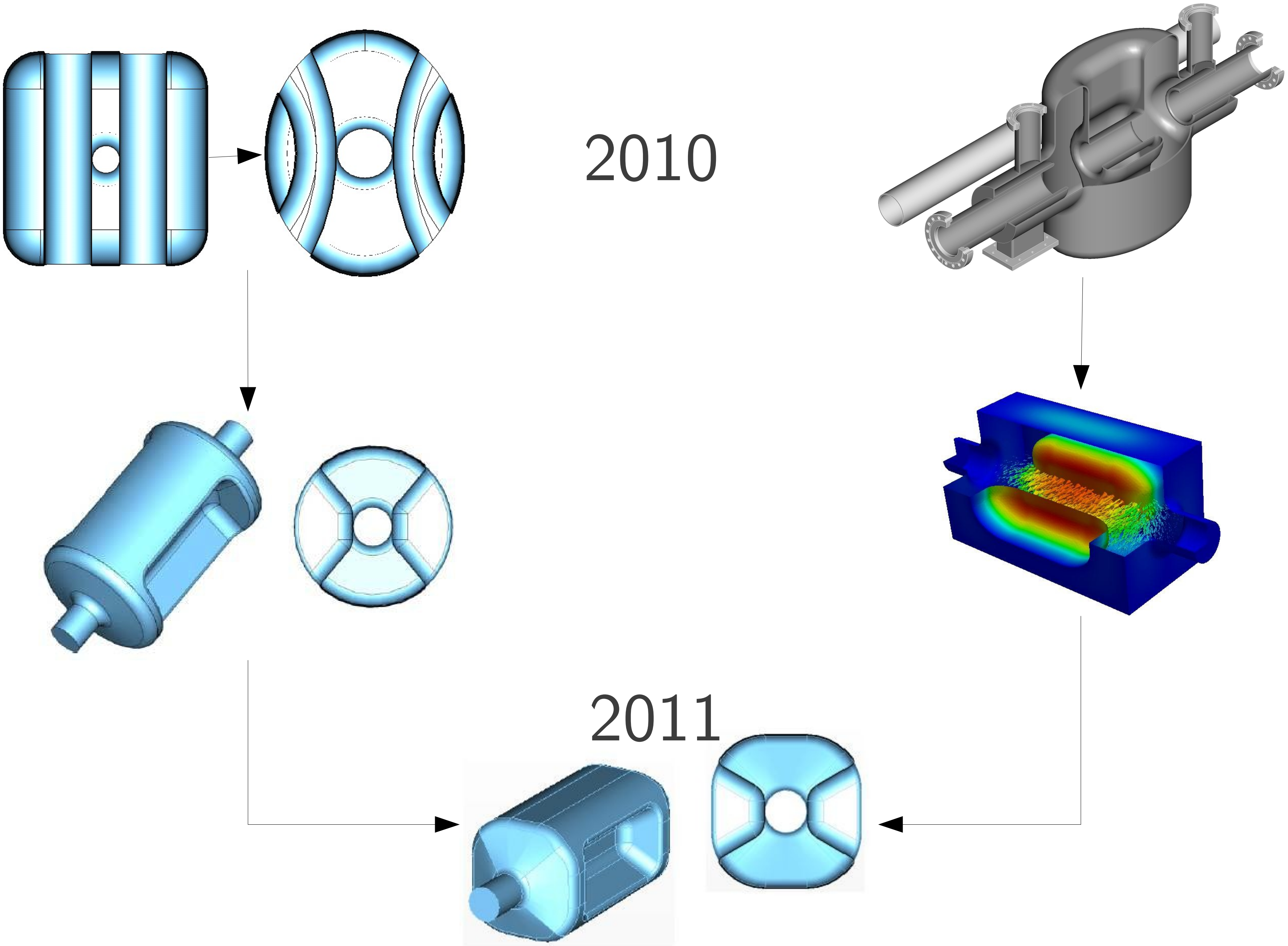
Bead-Pull



More measurements to follow

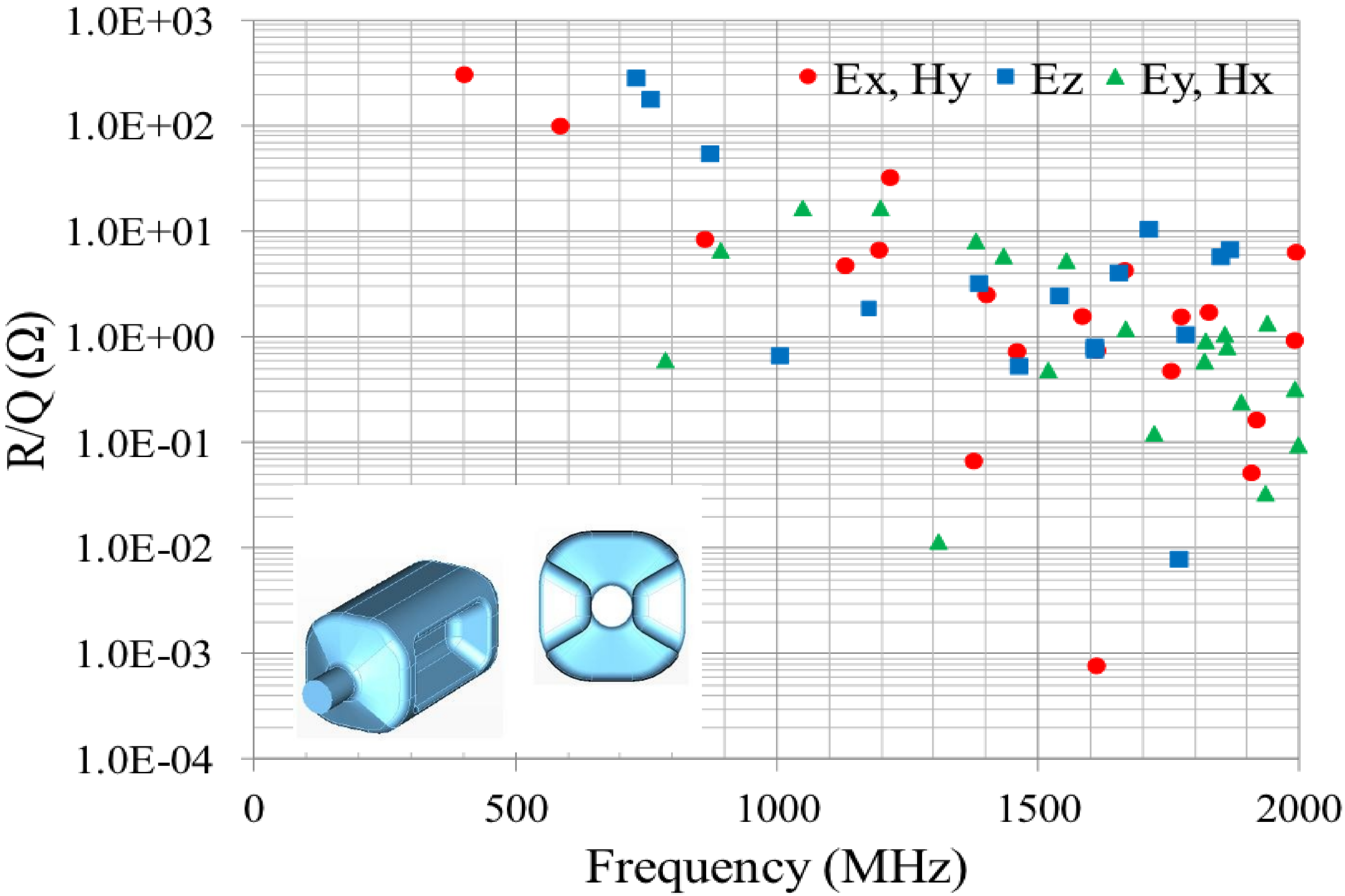
ODU & SLAC Design(s)

Courtesy J. Delayan, Z. Li



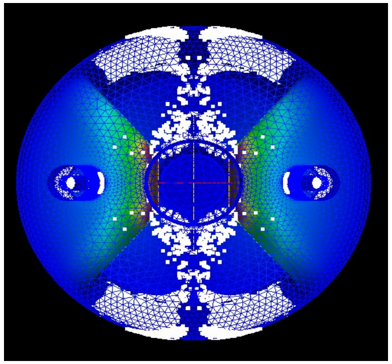
HOMs, ODU-SLAC

Courtesy J. Delayan

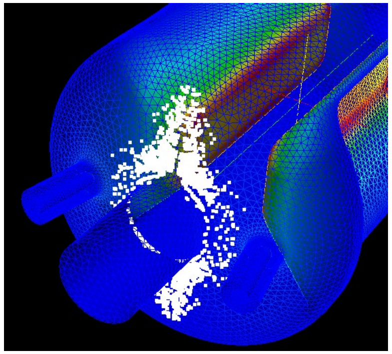


Double Ridge, Multipacting

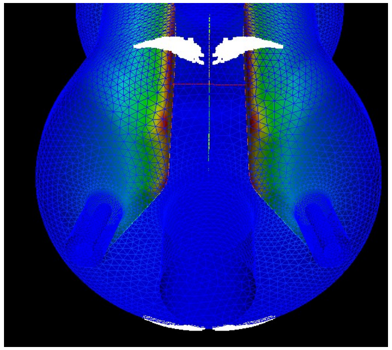
Courtesy J. Delayan, Z. Li



Moderate multipacting observed between 0.06-0.1 MV



Strong multipacting observed at beam pipe, 0.65-0.85 MV

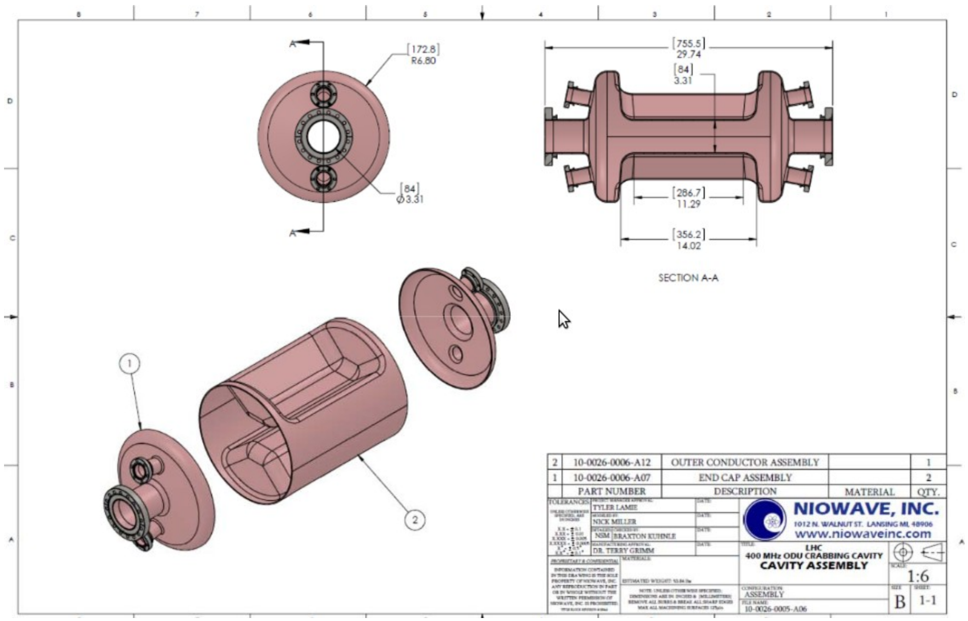


Weak multipacting 3-4 MV

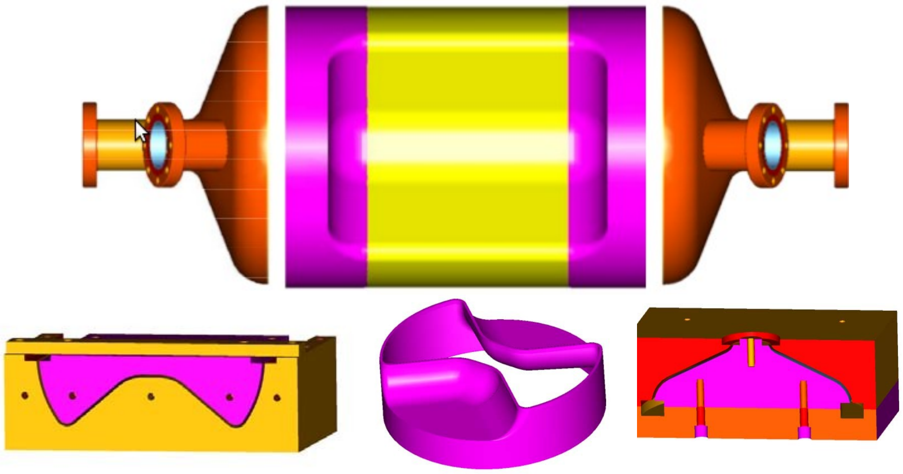
Also, strong multipacting in the coaxial couplers

Double Ridge Fabrication

Courtesy J. Delayan, Niowave

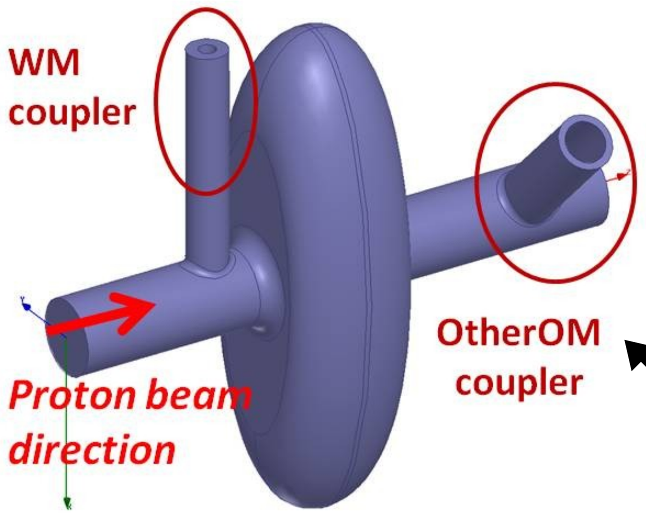


Niowave-STTR, Phase I



SLIM CAVITY, 800 MHz

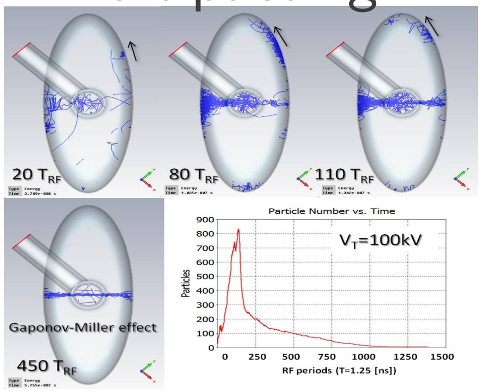
Courtesy L. Ficcadenti

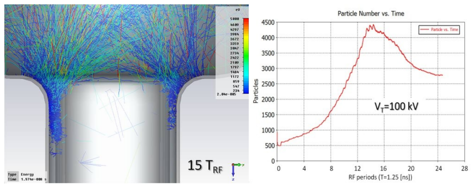


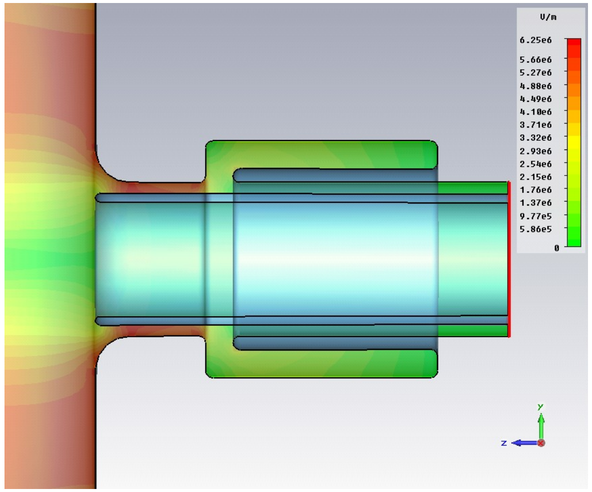
Strong HOM damping with single coupler & beam line coaxial line

But fundamental mode power is too high

Multipacting



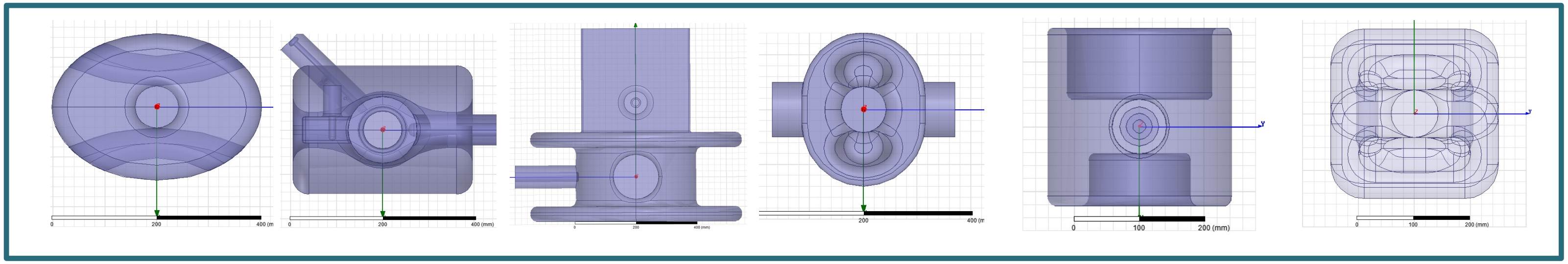




$\lambda/4$ choke similar to SLAC design can be used to reduce the fundamental power to HOM coupler

RF Non-Linearity, Contd.

Courtesy A. Grudiev, R. deMaria, J. Barranco



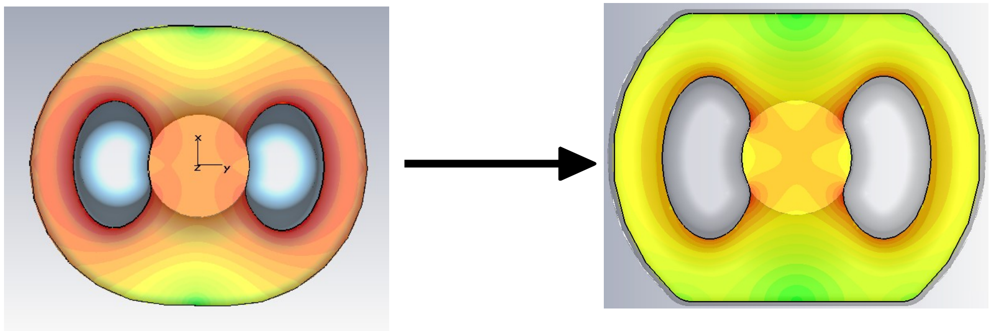
	ODUCAV	SRHW	KEKCAV	UKCAV	QWAVER	FRSCAV
Vz(x=0) [kV]	0.0	-2.1 - 2.5i	-4 +**1378**i	0.0	0 +85.7i	-0.1 -0.2i
Vx [MV]	5	5	5	5	5	5
B(2) [mTm/m]	0	0 -0.04i	-32.7 - 0.1i	0.02 + 0i	25 + 0i	0 +**108**i
B(3) [mTm/m2]	1250 + 0i	229 + 0i	250 - 0i	**2452** - 0.5i	464 + 0i	-233 +1i
B(4) [mTm/m3]	0	0	266 - 5i	0	540 +0i	-189 -**14209**i

Linear tune shifts $< \xi_{bb}$: 2 x 10^{-2}

Non-linear effects (b3, b4) → Negligible

RF Non-Linearity

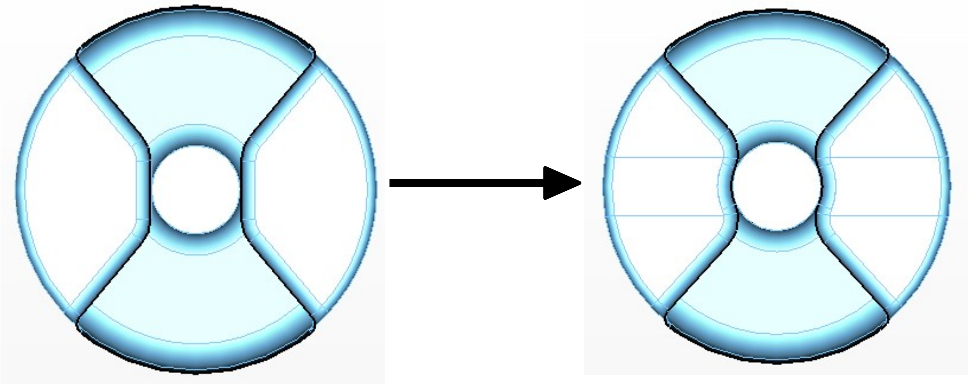
Courtesy G. Burt, J. Delayan

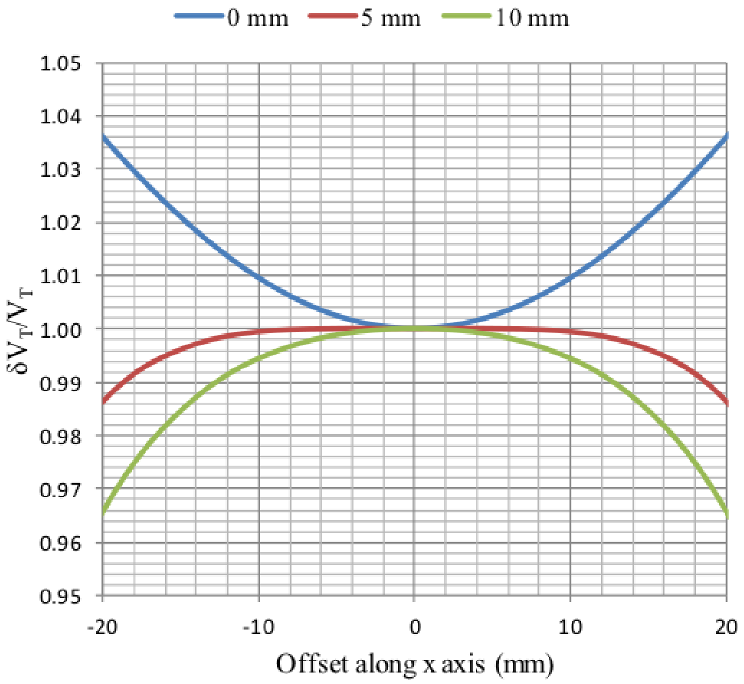


Voltage deviation over 5mm:

Horizontal: 20% → 5%

Vertical: x2 → 10%



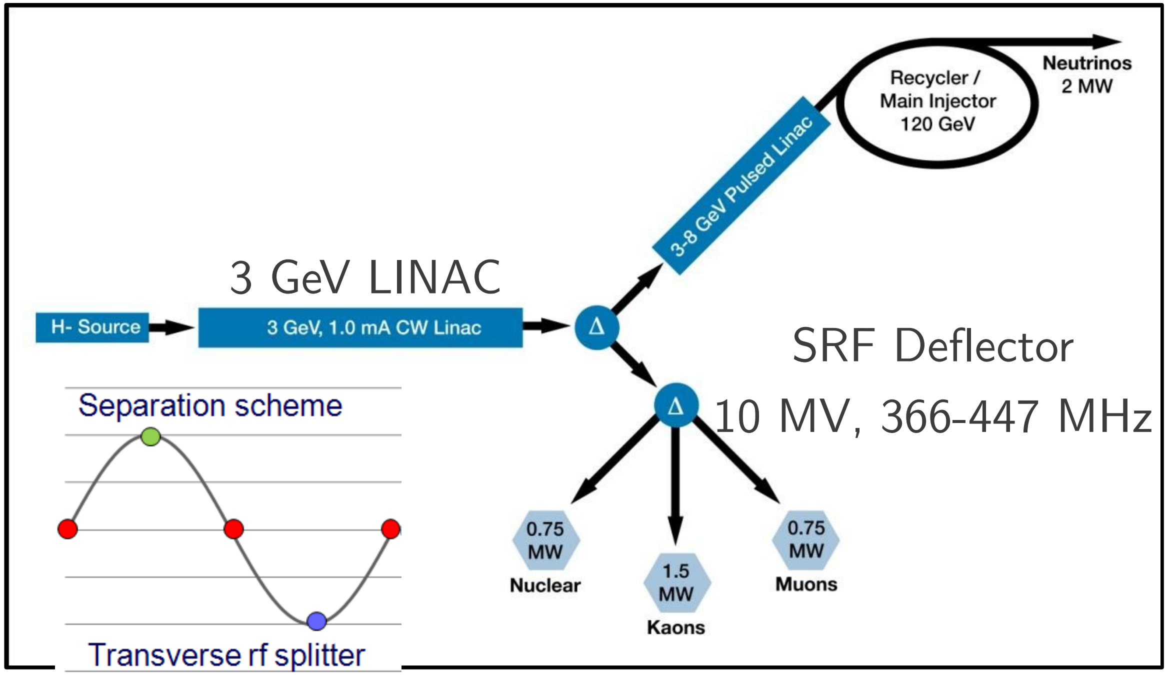


Tuning possible to suppress

RF multipoles once specs are know

PROJECTX SYNERGY

Courtesy M. Champion, Y. Yakovlev



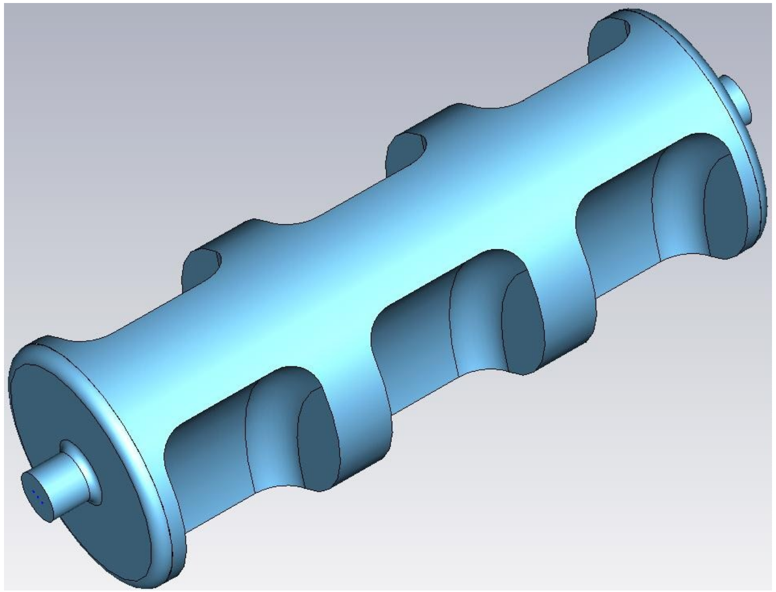
3 GeV LINAC

SRF Deflector

10 MV, 366-447 MHz

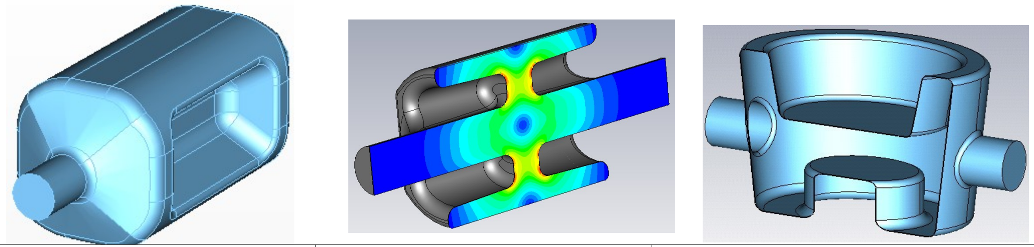
Mode I	TE113
Freq	447 MHz
R/Q	500 Ω
Epk	34 MV/m
Bpk	74 mT
Aperture	75 mm

LHC Type Concept(s)



Performance Chart

Kick Voltage: 3 MV, 400 MHz

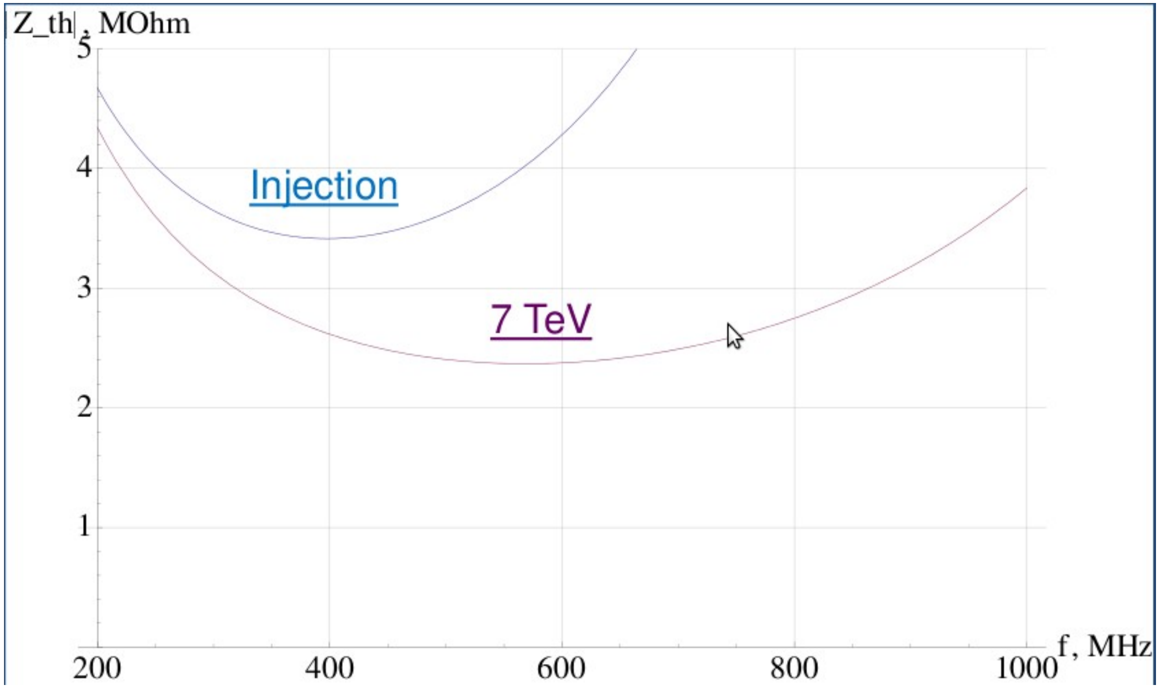


Geometrical

RF

	Modified PB (ODU)	4-Rod (UK)	¼ Wave (BNL)
Cavity Radius [mm]	**147.5**	**143/118**	**142/122**
Cavity length [mm]	597	500	380
Beam Pipe [mm]	84	84	84
Peak E-Field	33	32	47
Peak B-Field	56	60.5	71
R_T/Q	287	915	318
Nearest Mode	584	371-378	575

IMPEDANCE THRESHOLDS

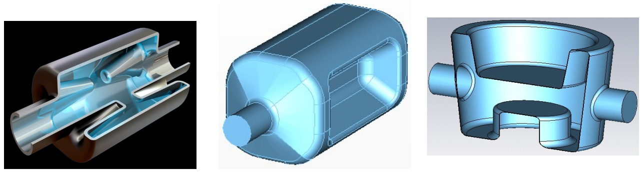


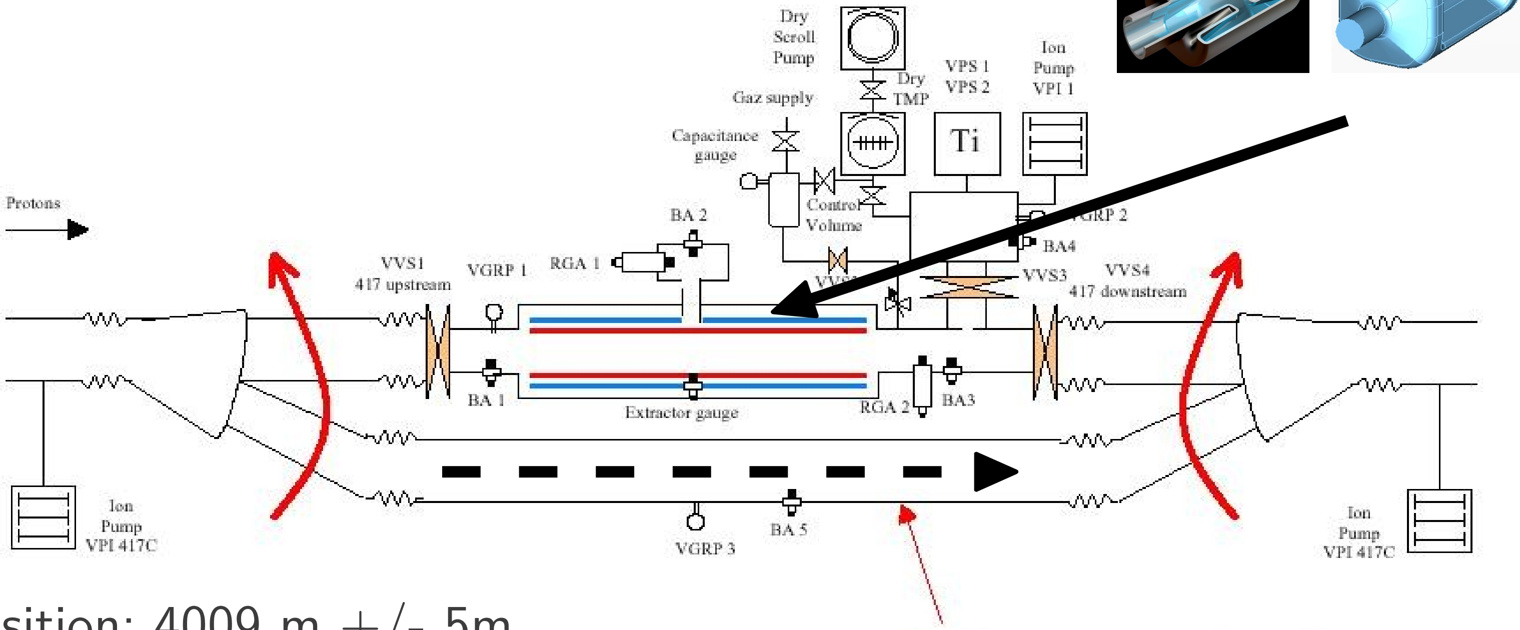
Longitudinal impedance
2.4 MΩ total, 7 TeV

Transverse impedance

Energy $\gamma m_p c^2$	**Beta-function** $\beta_{x,y}$	**Impedance** $-\mathrm{Re}\, Z_{\mathrm{th}}$
450 GeV	150 m	2.7 MOhm/m
7 TeV	4 km	1.5 Mohm/m

SPS As a Testbed





Default vacuum chamber

Long. Position: 4009 m +/- 5m

Total length: 10.72 m

βx, βy: 30.3m, 76.8m

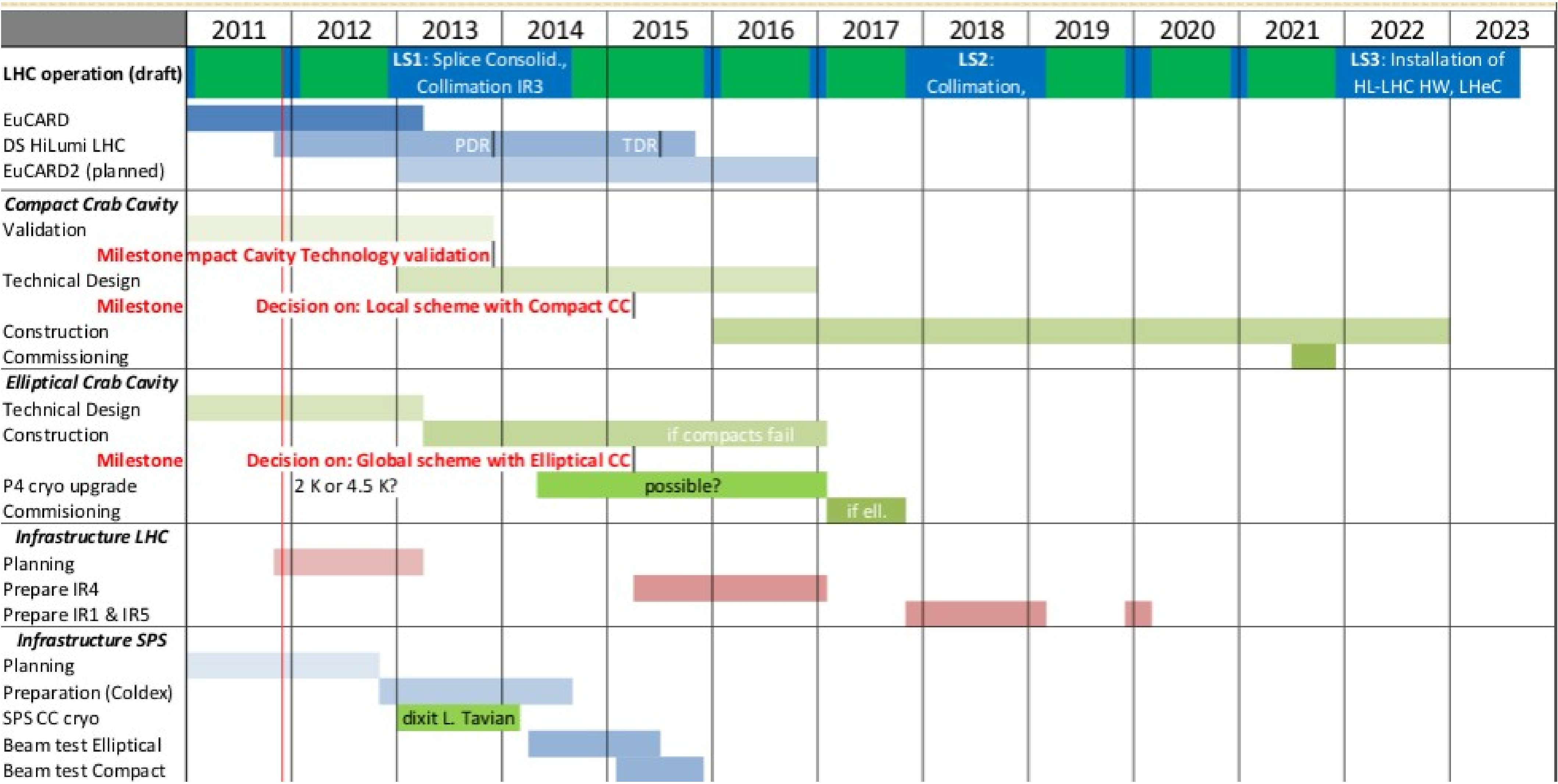
Cavity validation with beam (field, ramping, RF controls, impedance)

Collimation, machine protection, cavity transparency

RF noise, emittance growth, non-linearities,

Instrumentation & interlocks

OVERALL PLANNING



Milestone 0: Cavity specifications document, April 2012

Milestone 1: Validation of compact cavities, ~Nov 2013

Milestone 2: Prototype cryomodule → SPS beam tests, 2015

FUTURE & CHALLENGES

RF Design

Cavity geometries almost in their final configuration

Focus on HOM damping, multipacting and mechanical analysis

Fabrication & VTA Testing

Field gradient demonstration (+ multipacting, mechanical effects etc..)

Niobium double rigde & 4-rod ready by end of 2012

Cu prototype for ¼ wave by fall 2012 (Nb ?)

Cryomodule(s)

Develop a strategy immediately for a cryostat

Potential involvement from CEA, CNRS & FNAL

Other applications

Momentum cleaning: $Qcc = (fcc/f0)\eta\delta$, need high freq

Emittance exchange (x-z), could it be used in SPS or LHC?

Compensate offset collisions due to beam loading for LHeC