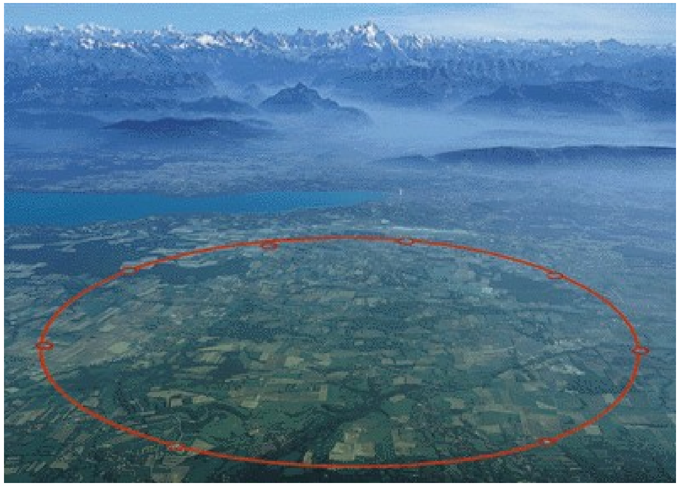
Crab Crossing for LHC Upgrade

Rama Calaga (on behalf of LHC-CC Collaboration)

SRF2011, July 29, 2011

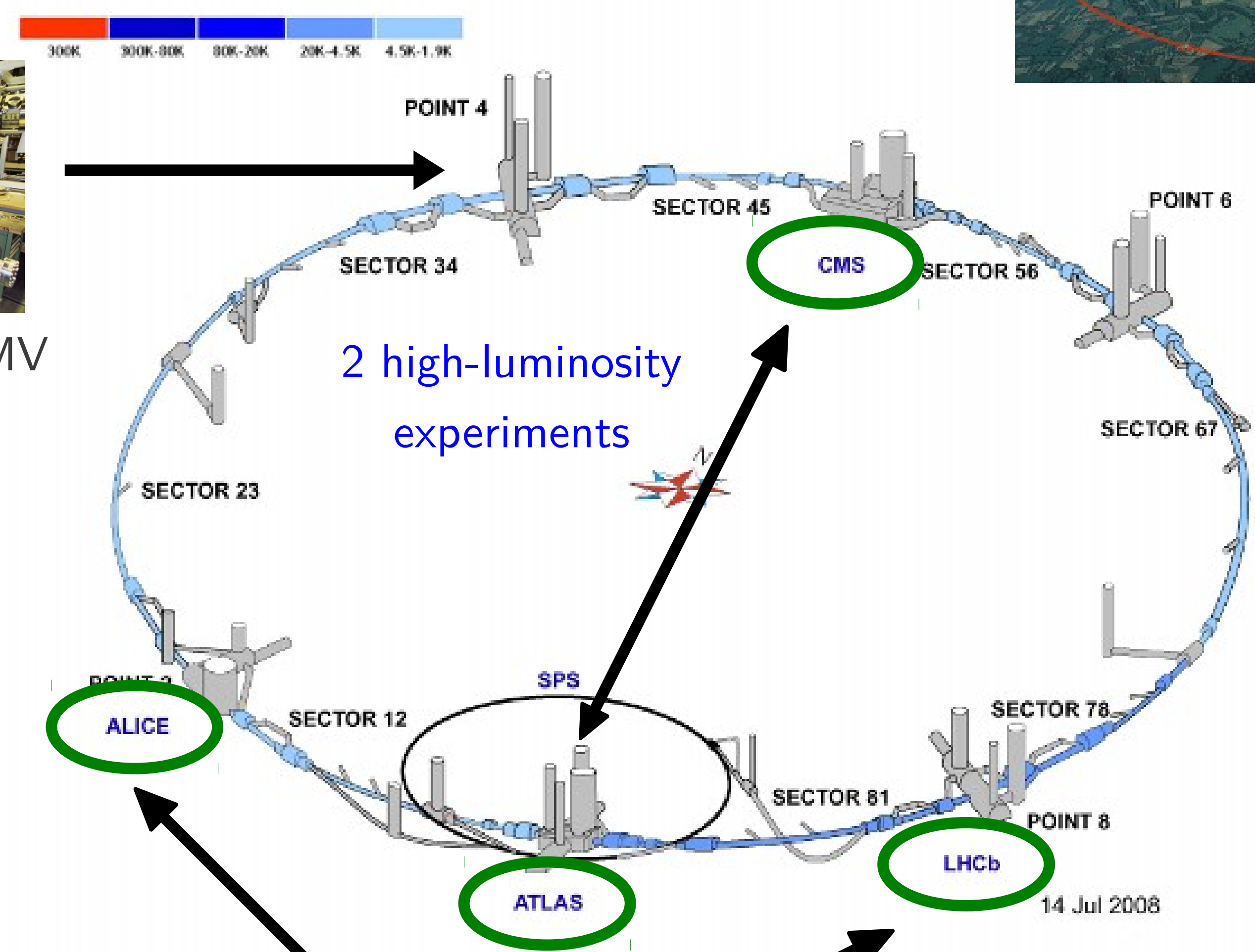
- LHC and its upgrade
- Evolution of technology concepts & studies
- Planning & future activities

The LHC

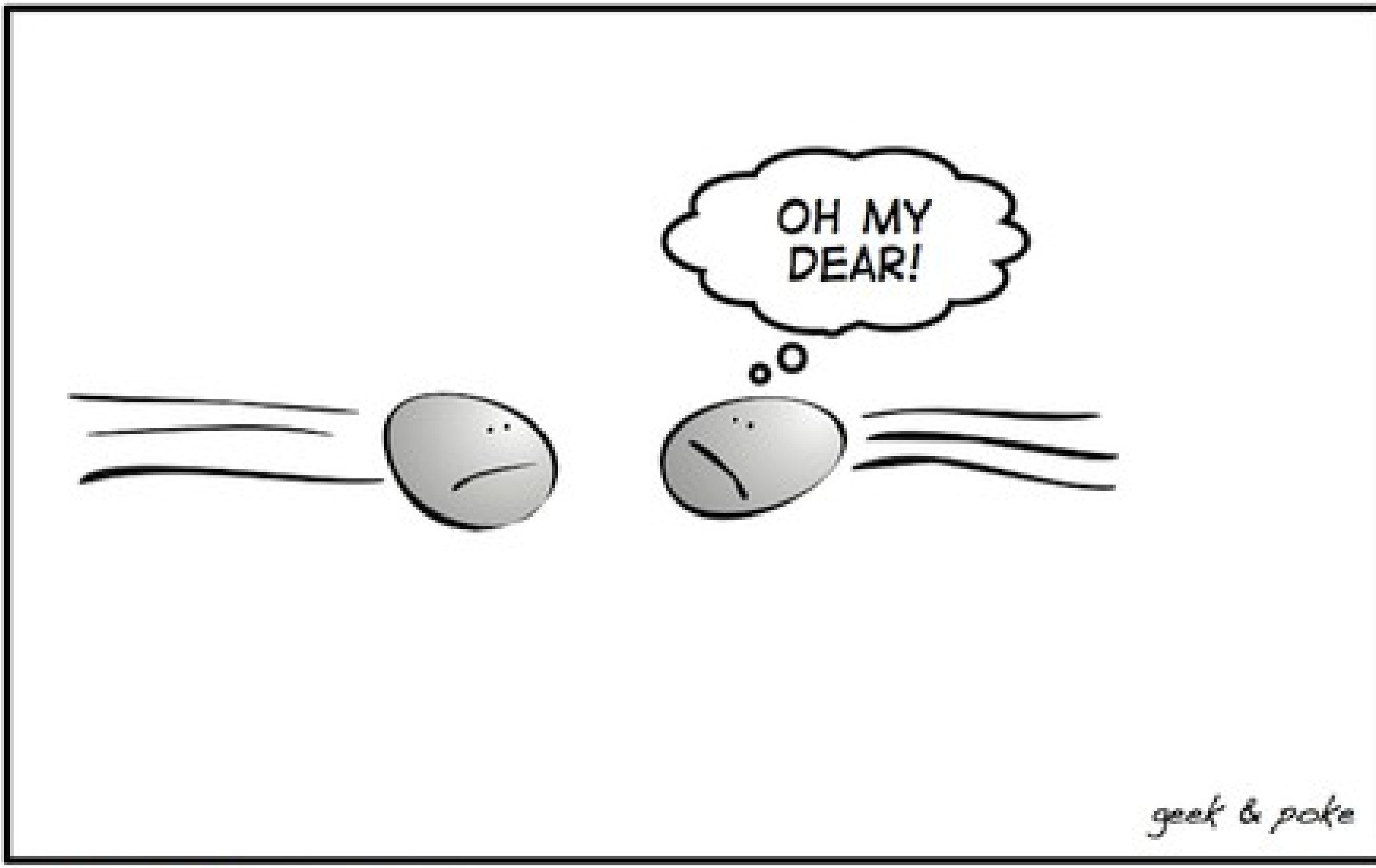


27 km @1.9K to accelerate protons to 7TeV

400 MHz SRF, 16MV



2 experiments to study
anti-matter & heavy ions



LATELY INSIDE THE LHC:
2 PROTONS 0.0000000000000000000001 SEC BEFORE THE COLLISION

...yet no Higgs or is there

http://www.nature.com/news/2011/110722/full/news.2011.435.html

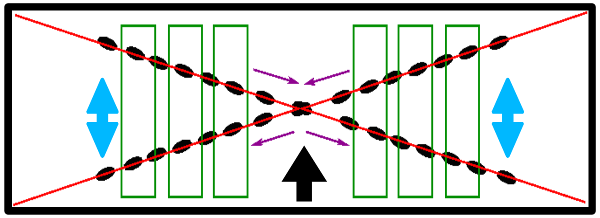
LHC: Today & Future

	Today	Design (2015)	Upgrade (2021)
Energy [TeV]	3.5	7.0	7.0
Intensity [x 10^{11}]	1.1-1.2	1.15	≥ 1.7
N. Emittance (μm)	2.2-2.5	3.75	≥ 3.75
β* (cm)	150	55	15
# of bunches	1380	2808	2808
L_{peak} [x 10^{34}]	0.19	1	~8*
L_{int} [fb^{-1}/yr]	~2	67	250

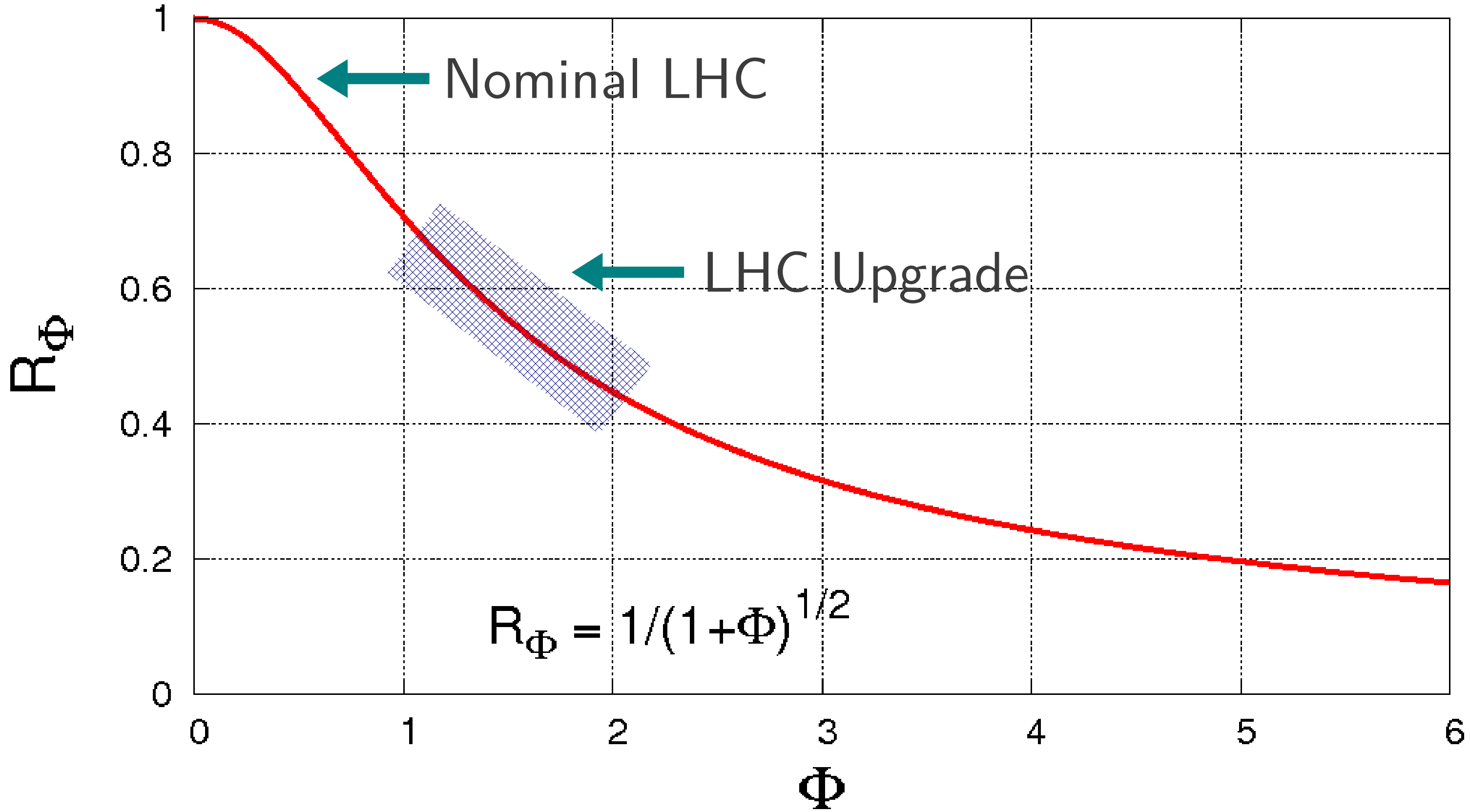
*Luminosity leveling → 5 x 10^{34} [cm^{-1} s^{-1}]

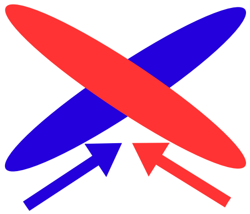
Ultimate goal by 2030: 3000 fb^{-1} (Radiation damage limit ~700 fb^{-1})

X-Angle & Reduction



32 Long-range /IP





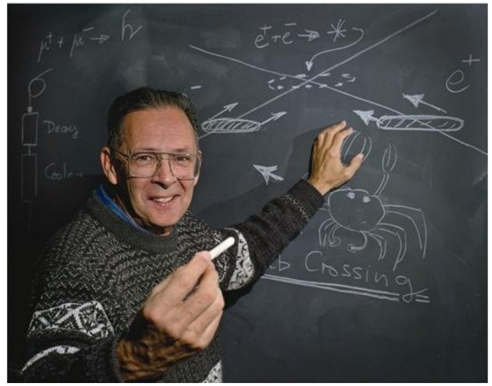
Inefficient overlap

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

$$V_{RF} \propto \frac{1}{\sigma_z^4} \quad \rightarrow \quad \text{Unfavorable voltage scaling}$$

$$V_{CRAB} \propto \theta_c \quad \rightarrow \quad \text{Effective recovery + lumi leveling}$$

Crab Crossing, Evolution



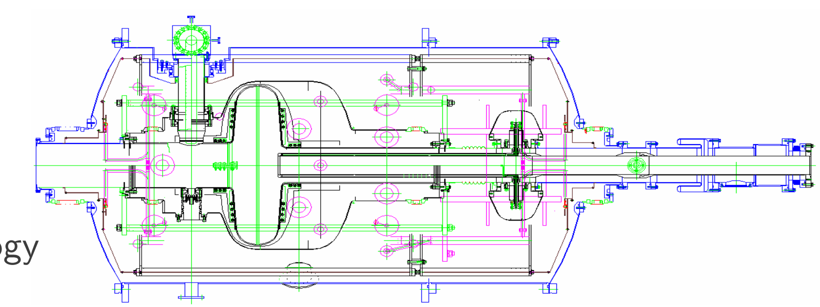
R. Palmer, 1988, LC

+20 yr

KEK-B

2007-2010

Elliptical Technology



+5-10 yrs

+10 yr

New Technology

Light Sources

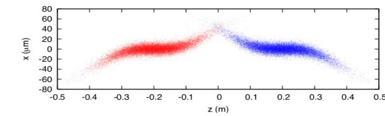
EIC, LC, HA

LHC

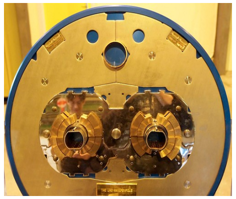
Proposed in 2005

Cavity Specification

	Baseline	Unit	LHC	KEK-B
	Frequency	MHz	400 (800)	509
RF	Deflecting Voltage	MV/Cav	5	2.0 (0.9-1.5)
	Peak E-field	MV/m	$<$ 45	28
	Peak B-field	mT	$<$ 80 mT	82 mT
Geometrical	Aperture (diameter)	mm	84	130
	Cav Outer Envelope	mm	$<$ 150	866/483
	Module length	m	$\sim$ 1m	1.5 m
	HV crossing	-	Desirable	N/A
Optics	β^* (IR1/IR5)	cm	15-25	63/0.7
	β crab	km	$\sim$ 5	0.2/0.04
	Non-linear harmonics	Units [10^{-4}]	2-3	N/A
	Impedance Budget	Longitudinal, Transverse	60kΩ, 2.5MΩ/m	-



$\sigma_z = 7.55$ cm

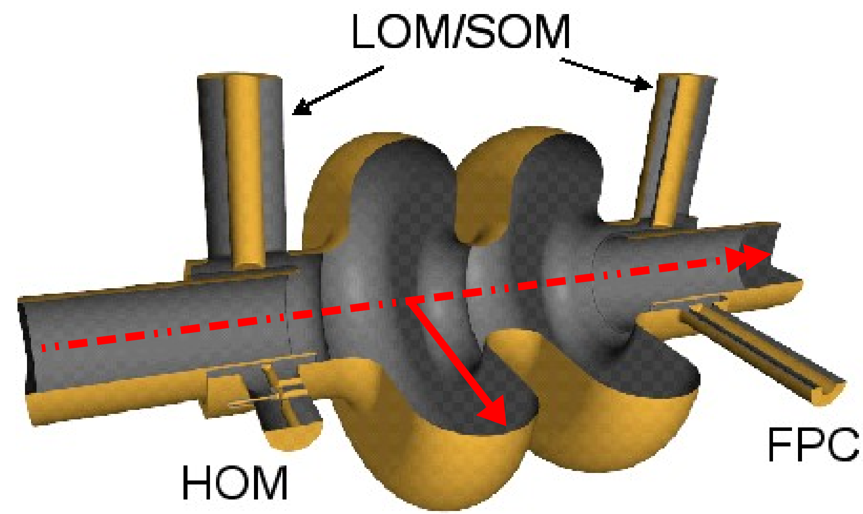


Beam-beam separation

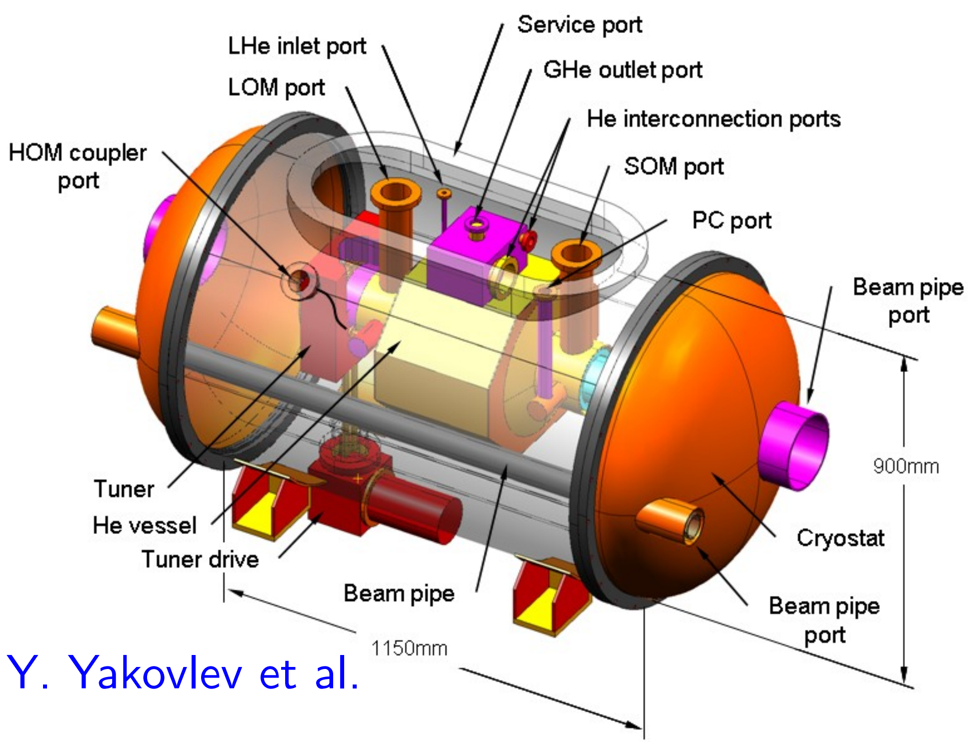
Two-Cell Elliptical

L. Xiao et al.

- Frequency: 800 MHz
- Strong HOM damping & compact



~250 mm outer radius



Y. Yakovlev et al.

Only fits in one location in the LHC (IR4)

Highly constrained

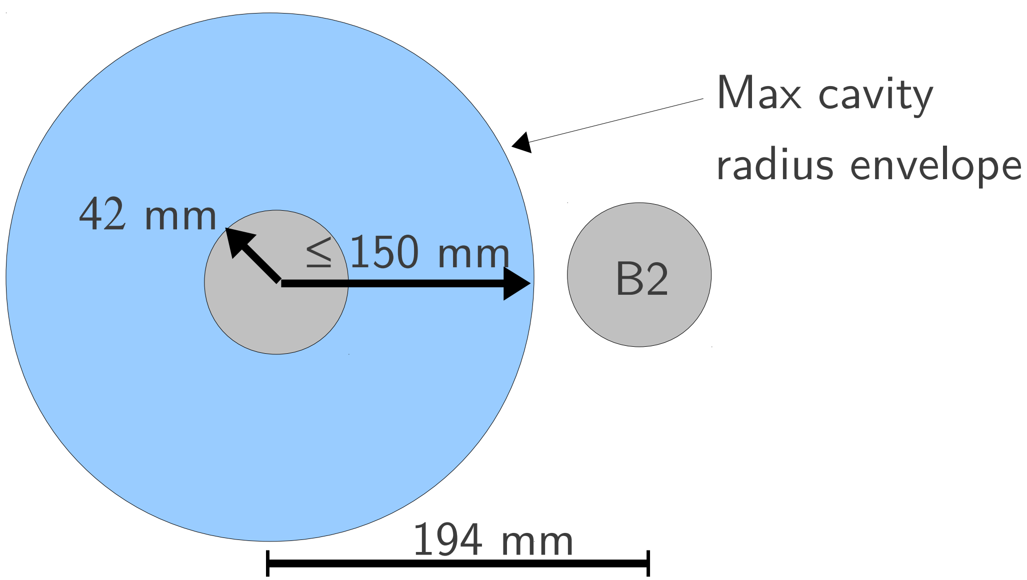
2009

Decision to focus on concepts with compact size

Frequency: 400 MHz

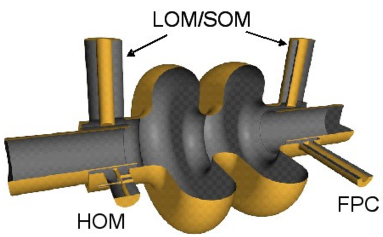
BP radius: 42 mm

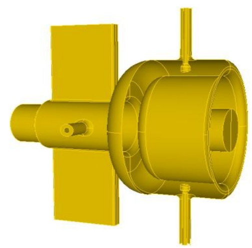
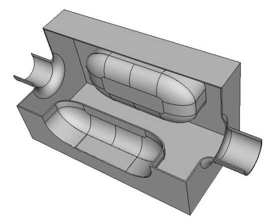
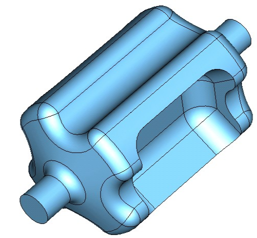
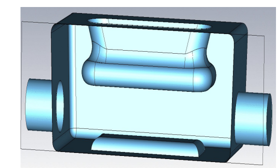
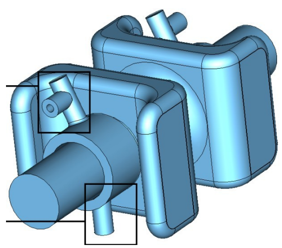
Outer envelope: < 150mm

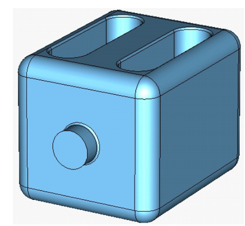
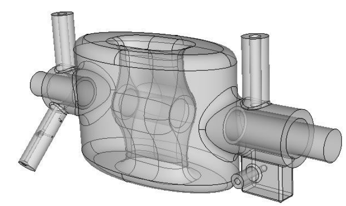
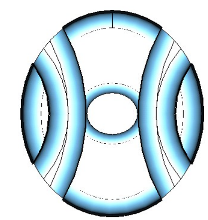
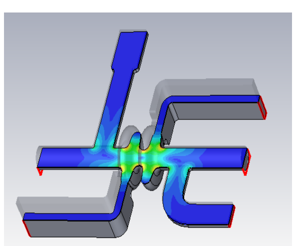
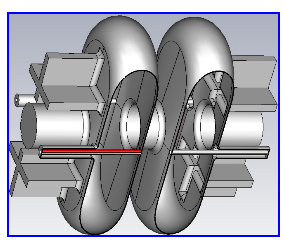
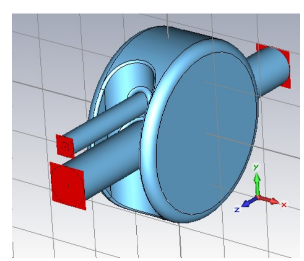
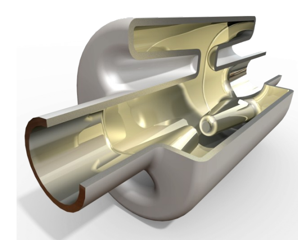
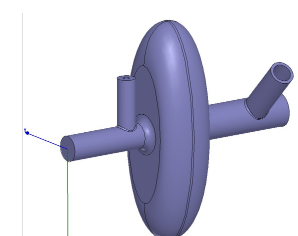


Worldwide Design Effort

~4yr of design evolution

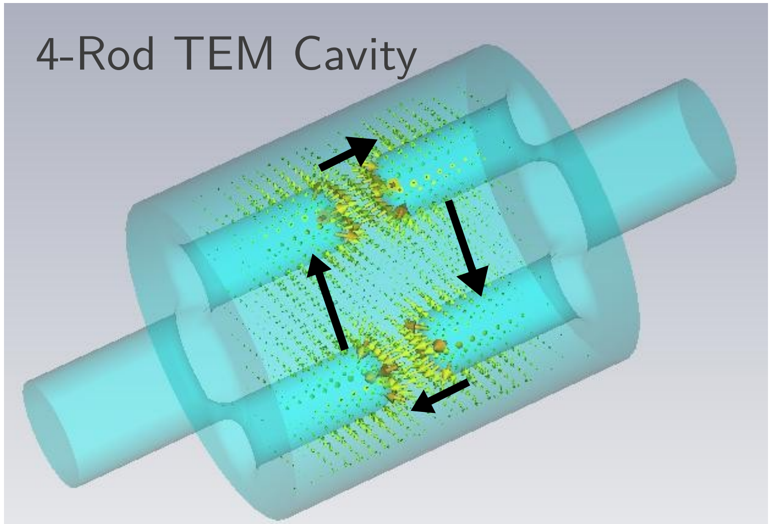


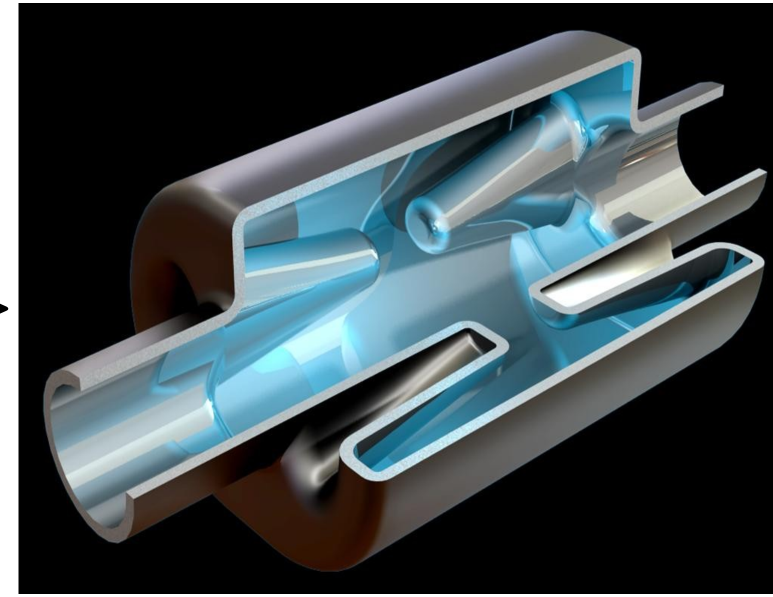
Exciting & rapid development of deflecting cavities
(BNL, CERN, CI-DL-LU, FNAL, KEK, ODU/JLAB, SLAC)

LU-DI (JLAB) Design

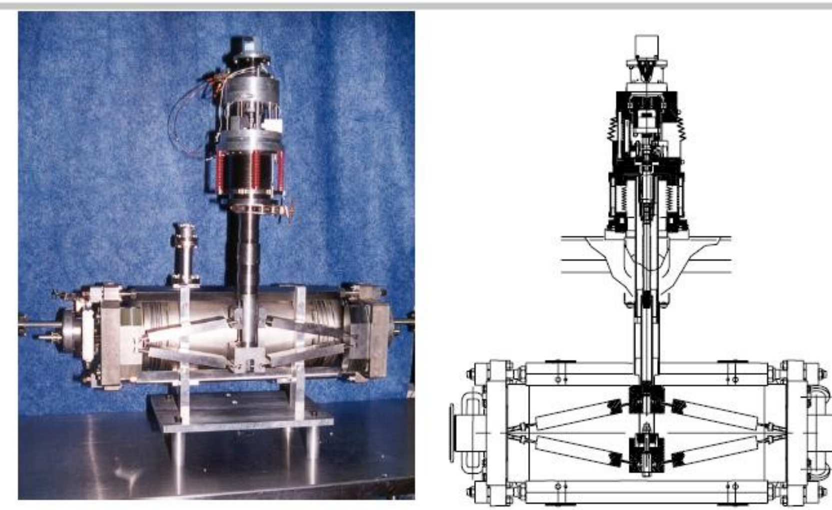


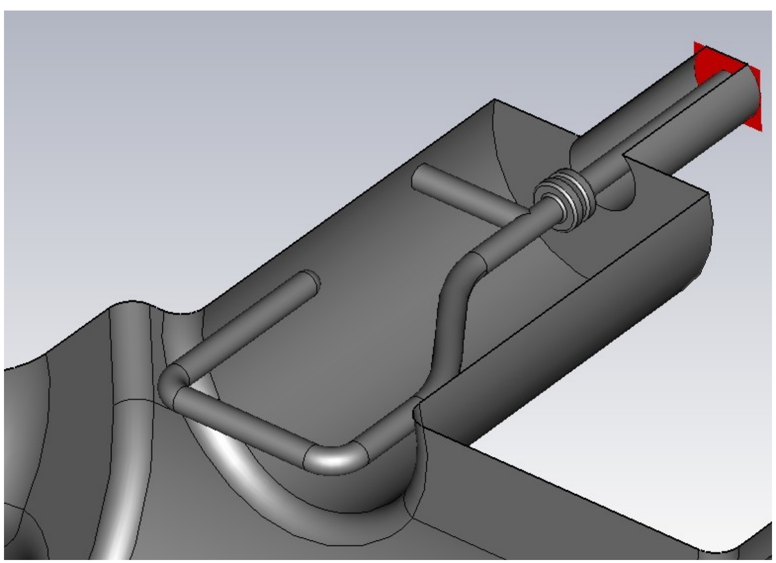
Towards

Conical rods



Prototype Tuner for CEBAF Ugrade



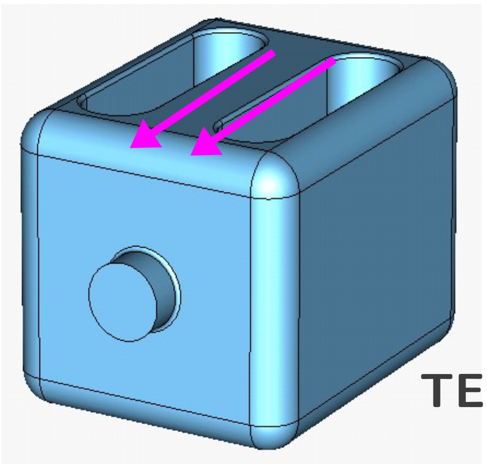


HOM Damping Concepts

Courtesy G. Burt et al.

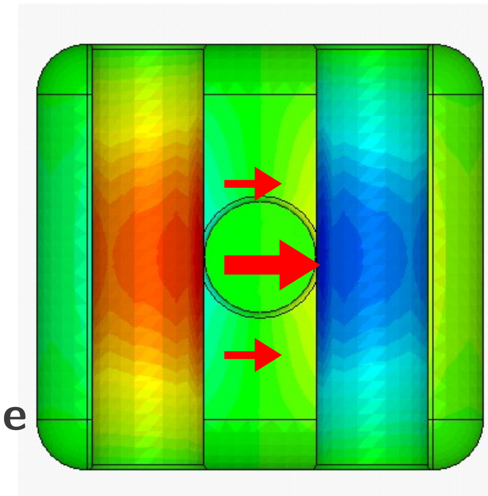
ODU-JLAB Design

Courtesy J. Delayen et al.

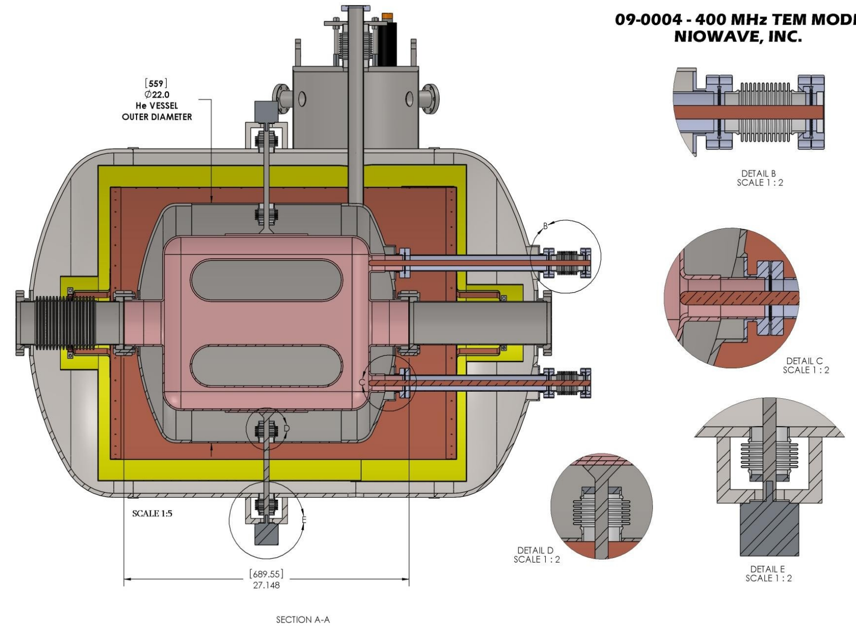


B-Field
Top plane

TEM-Mode



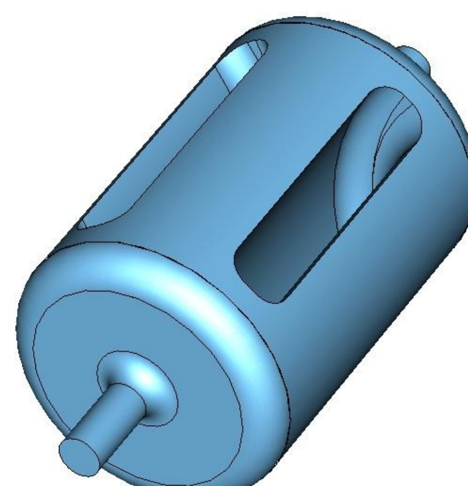
E-Field deflection
Mid plane



Niowave-STTR, Phase I

Improved properties
Cylindrical shape

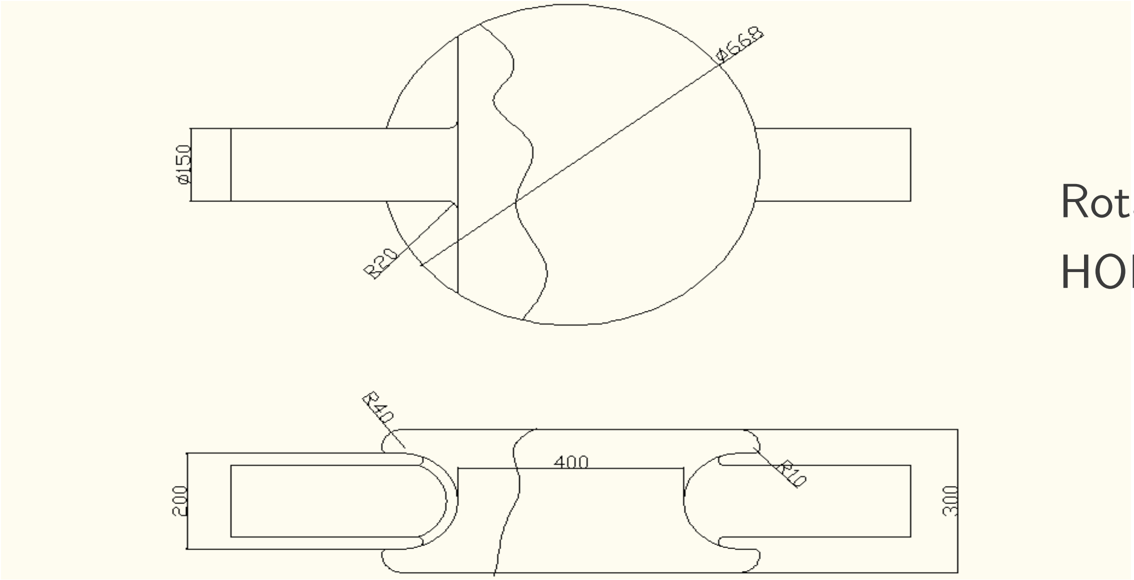
Fewer HOM modes



Phase II approved
For building cavity prototype
(ODU-Niowave)

KEK-Kota Design

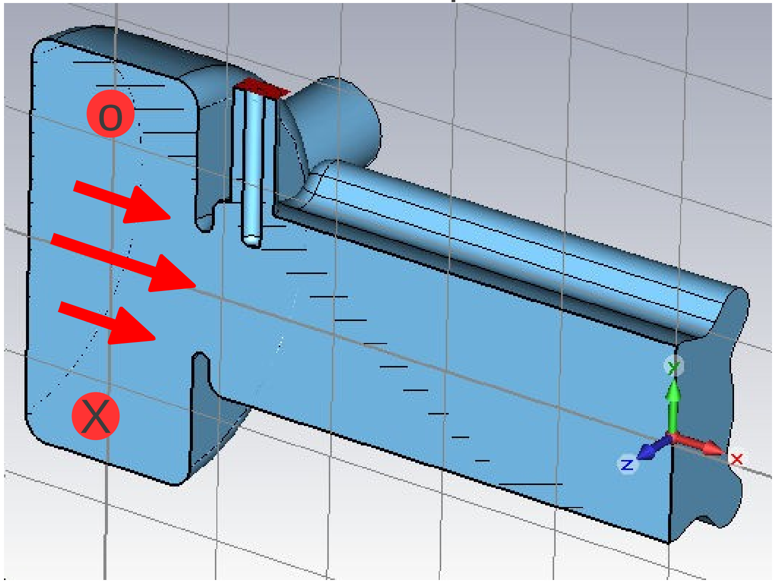
Courtesy K. Nakanishi et al.



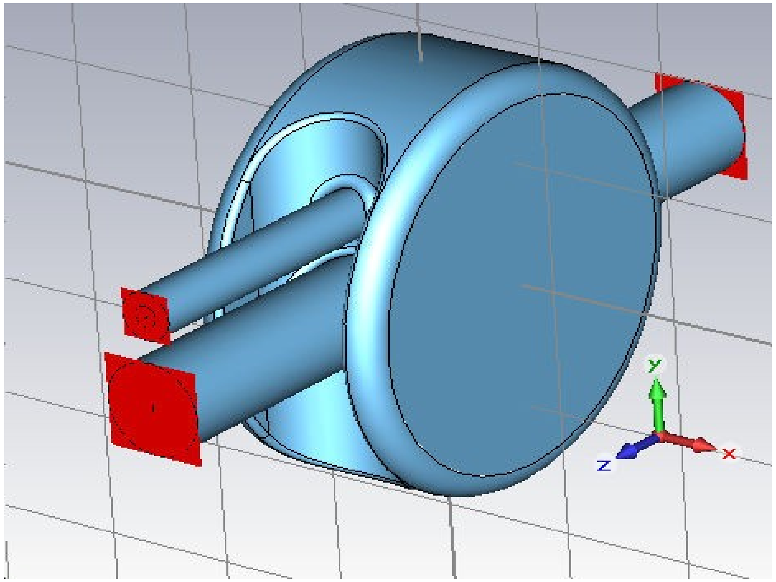
Rotated Pillbox with shielding cones

HOM studies and damping scheme underway

Power Coupler

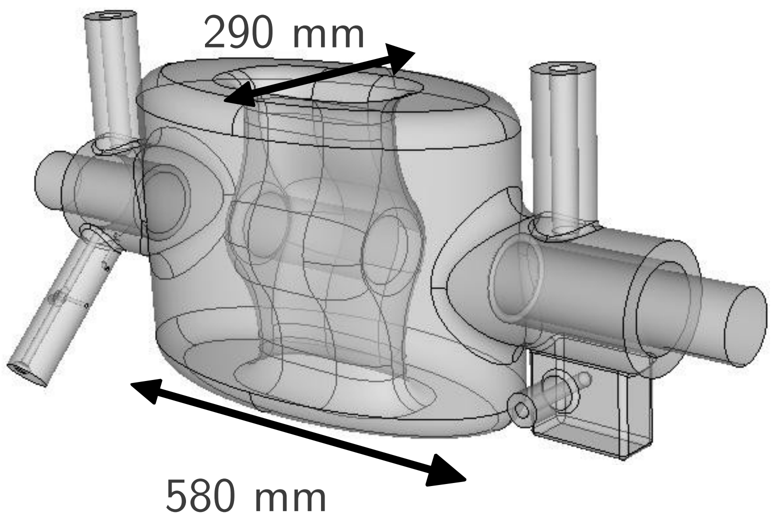


HOM Damping



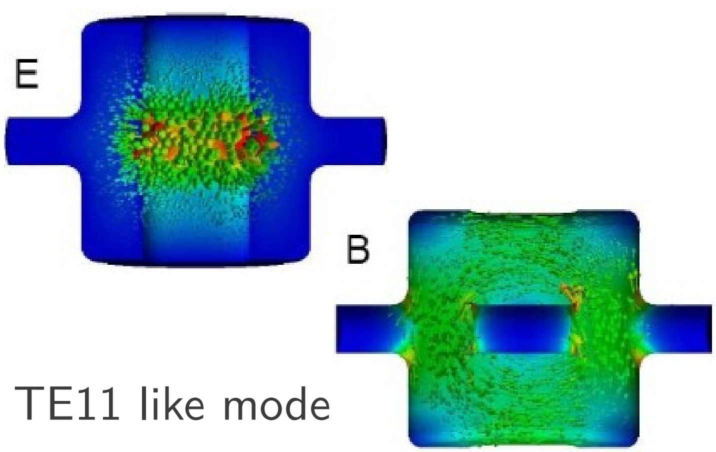
SLAC-LARP Design

Zenghai Li et al.



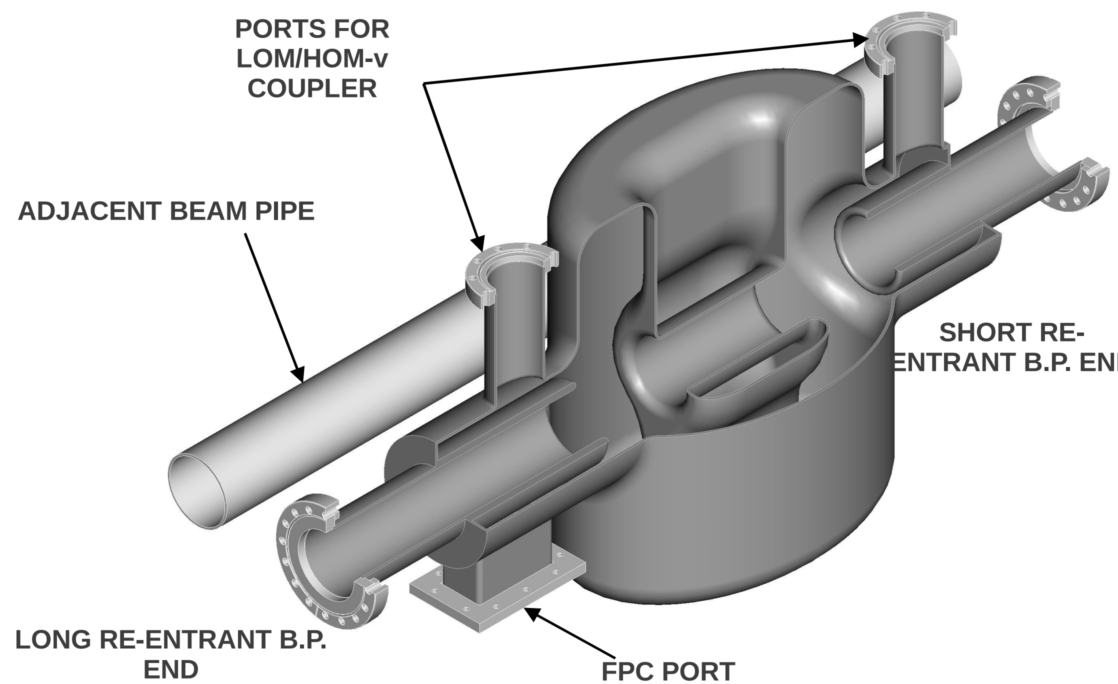
RF design: supported by LARP

Mechanical design: supported by Phase I SBIR

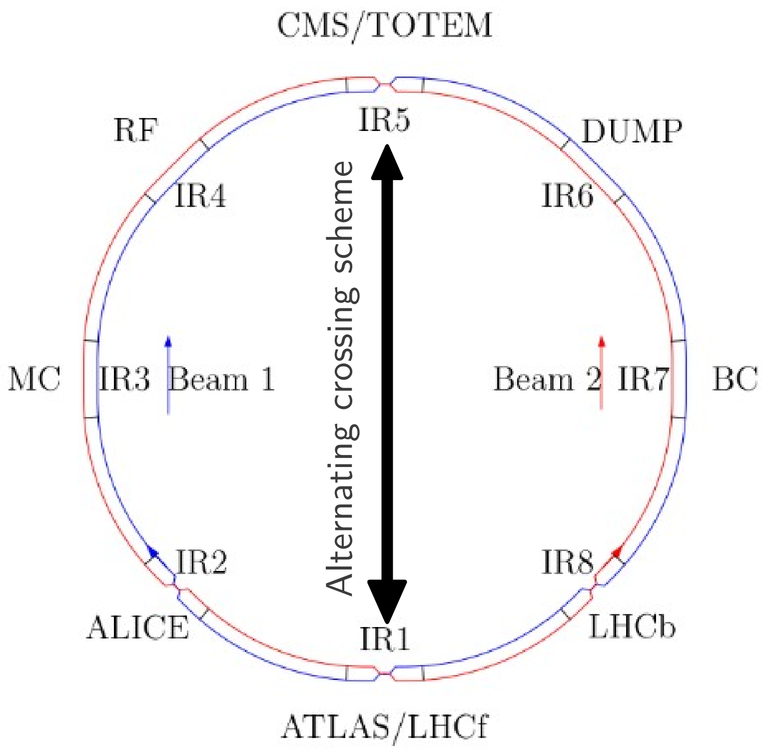


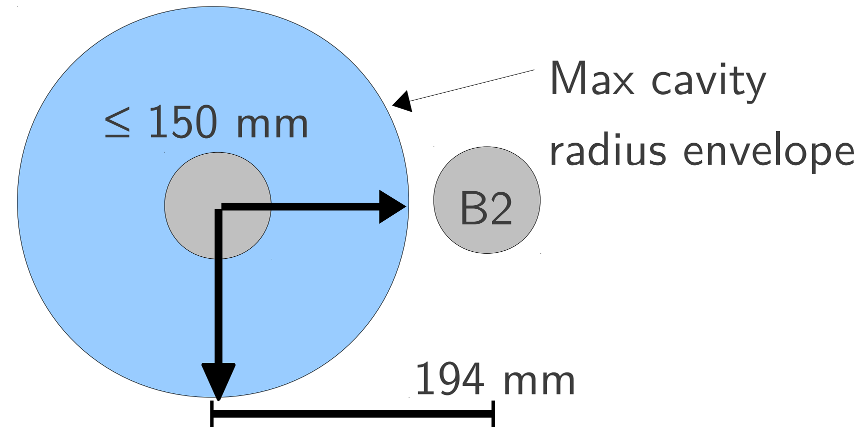
TE11 like mode

B-field deflection



Dual Crossing Constraint





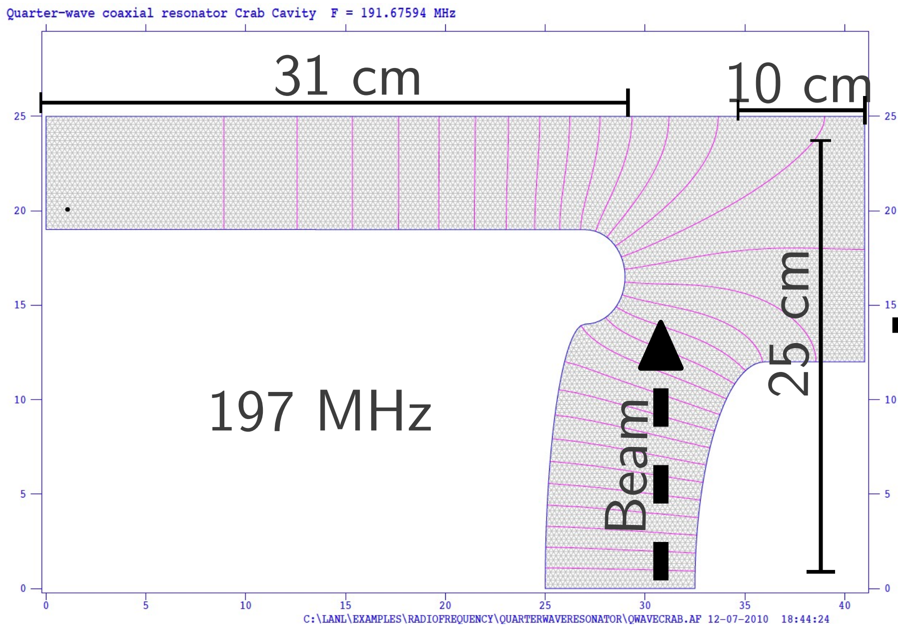
Parallel bar & ½-Wave cavities fit only for horizontal crossing!

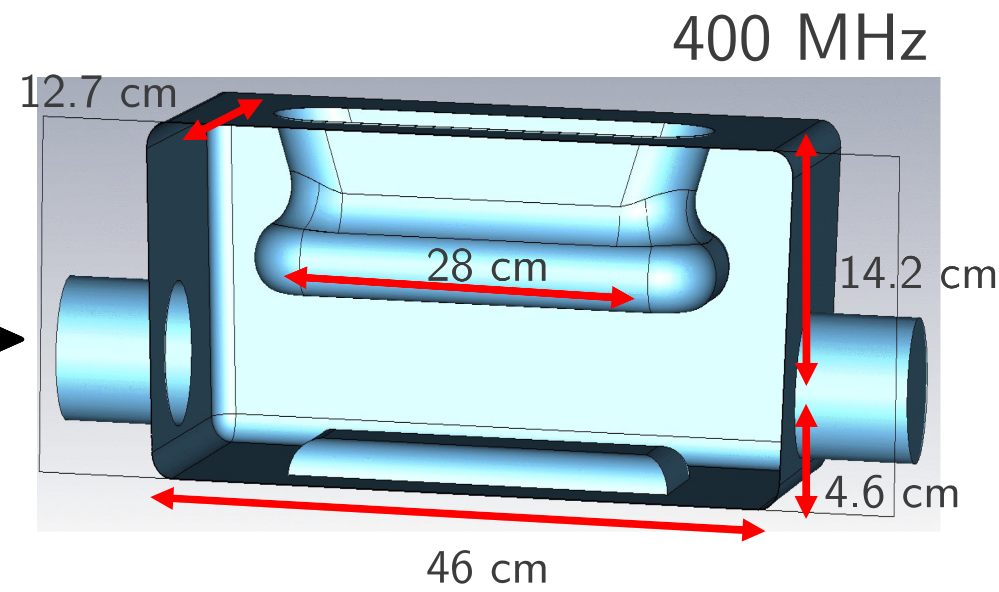
- Only works for one experiment

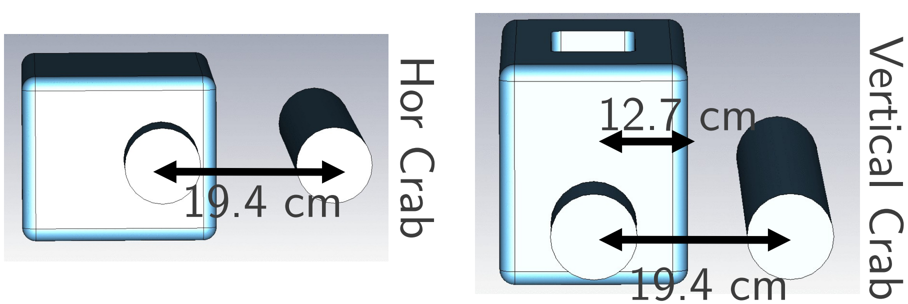
In 2010, design efforts to focus on dual crossing (HV)

¼ Wave Concept

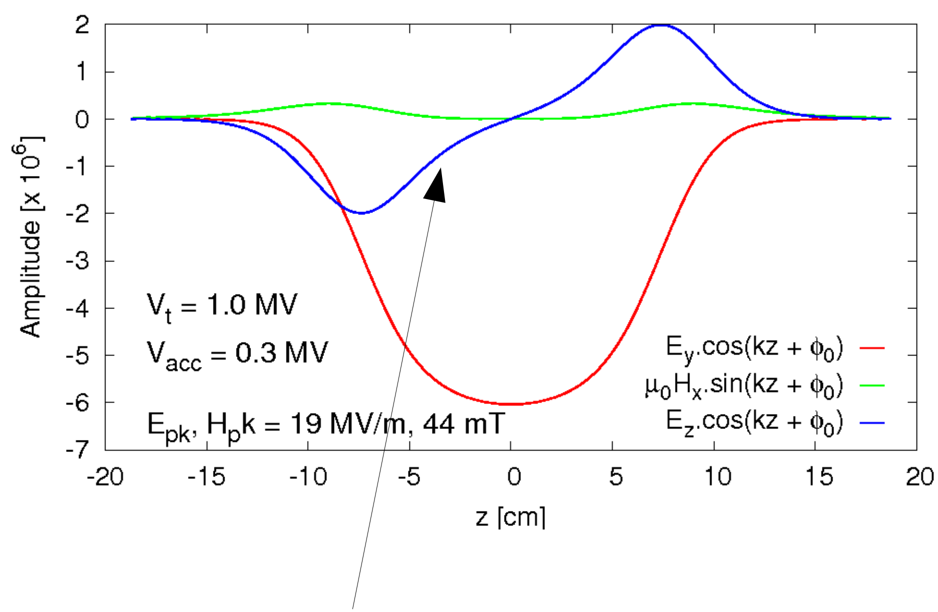
Ben-Zvi/Calaga







Ultra compact & fits HV crossing

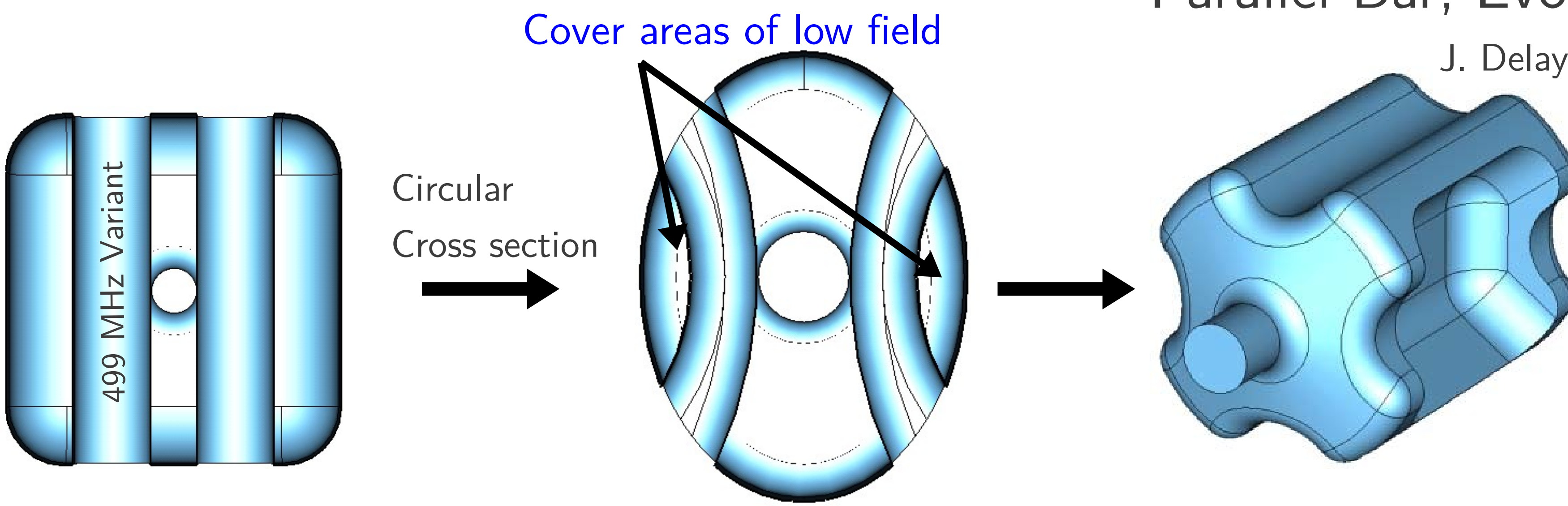


Accelerating voltage (need for supression)

Most Recently

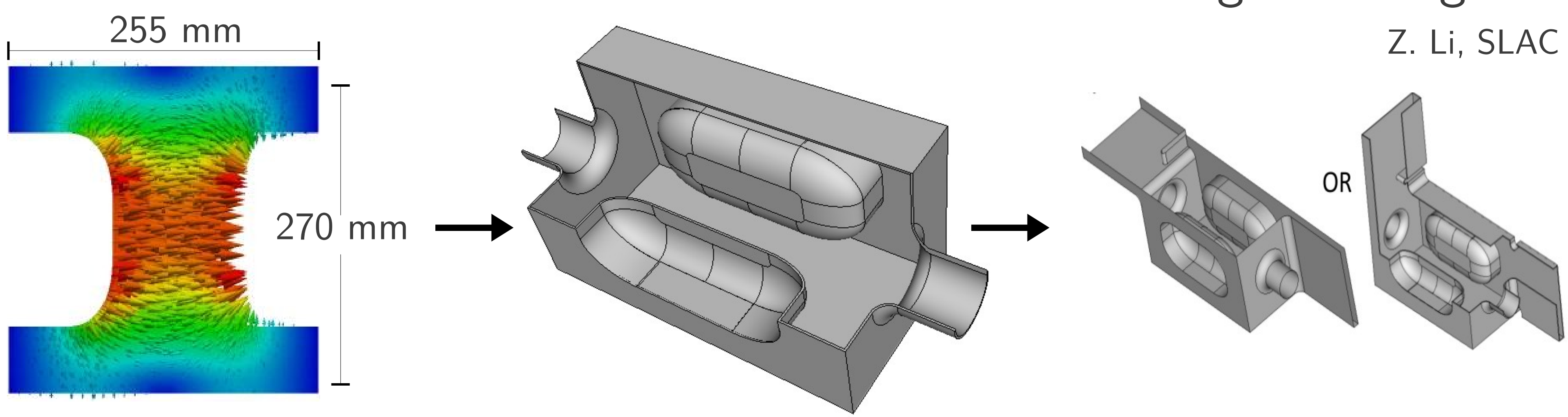
Parallel Bar, Evolution

J. Delayen, ODU



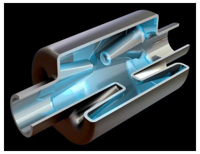
HWR → Ridged Waveguide

Z. Li, SLAC



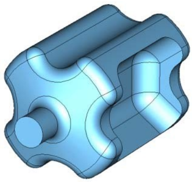
Present Status

4-rod design has advanced

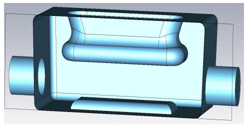


Engineering meeting for fabrication (mid-August)

Merging of efforts between ODU & SLAC



Parallel bar & ridged waveguide concepts → common design



¼ wave concept to continue towards final design

$V_T = 2.5$ MV	4-Rod	Double Ridge	1/4-Wave
Epk	33 MV/m	25 MV/m	48 MV/m
Bpk	49 mT	55 mT	110 mT
R/Q⊥	953 Ω	285 Ω	264 Ω
1^{st} HOM	375 MHz	619 MHz	675 MHz

Some Key Issues

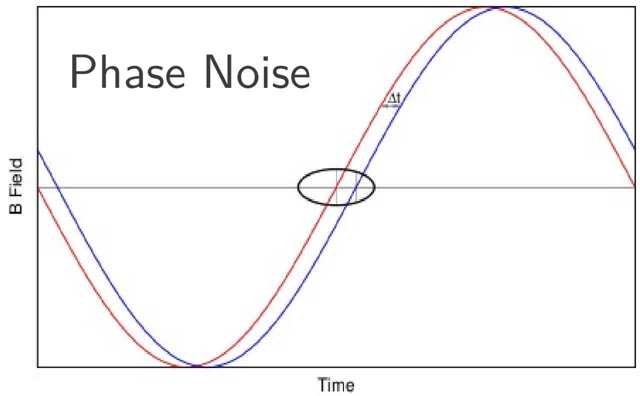
Beyond the cavity technology:

a. RF Phase noise $\rightarrow$ emittance blowup

b. Abrupt cavity failures $\rightarrow$ Machine damage

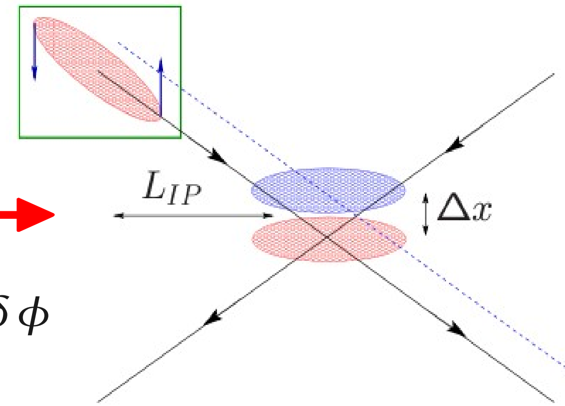
c. Impedance $\rightarrow$ beam instabilities

Crab Phase Noise



IP Offsets

$$\Delta x_{IP} = \frac{c\,\theta}{\omega_{RF}}\,\delta\phi$$



$$\delta\phi_{crab} \leq \frac{4\pi\,\Delta x_{max}}{\lambda_{RF}\,\theta_c} \qquad (\Delta x_{max} \sim 10\ \text{nm})$$

KEKB observations → Modulated noise 30 Hz - 32 kHz

Weak-strong beam-beam simulations ≤ 0.1σ (10%/hr)

Strong-strong BB simulations ≤ 0.02σ.(τ)

Dedicated measurements with induced noise in KEK ≤ 0.03^0

<u>LHC measurements</u> with beam-beam & damper noise planned for 2011-12

Machine Protection

Quench limit

Few mJ

Requirement

Stay above the 3-turn beam-abort threshold

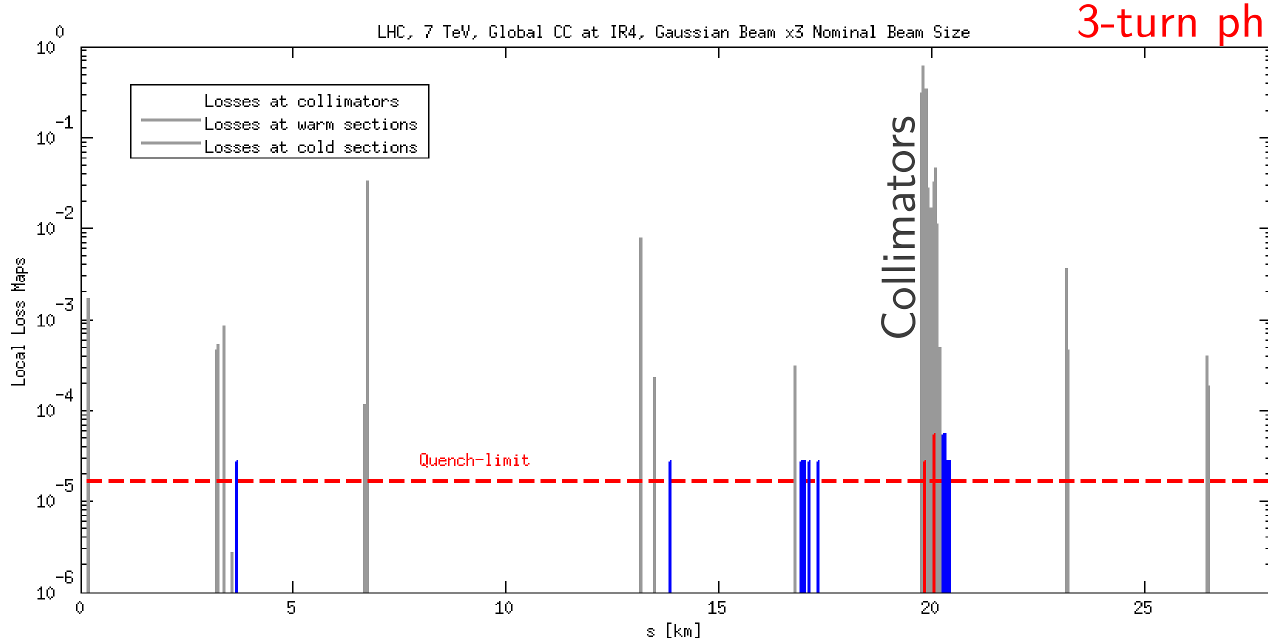
Tracking studies

Nominal LHC $\rightarrow$ Losses due 1-turn voltage/phase failure is non-issue

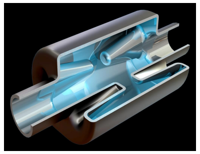
$\rightarrow$ Additional checks needed for different distributions

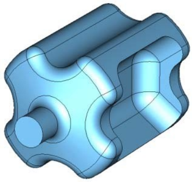
Upgrade optics (SLHC v3) under study

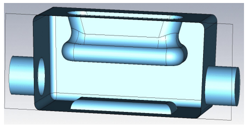
3-turn phase failure by 90^0

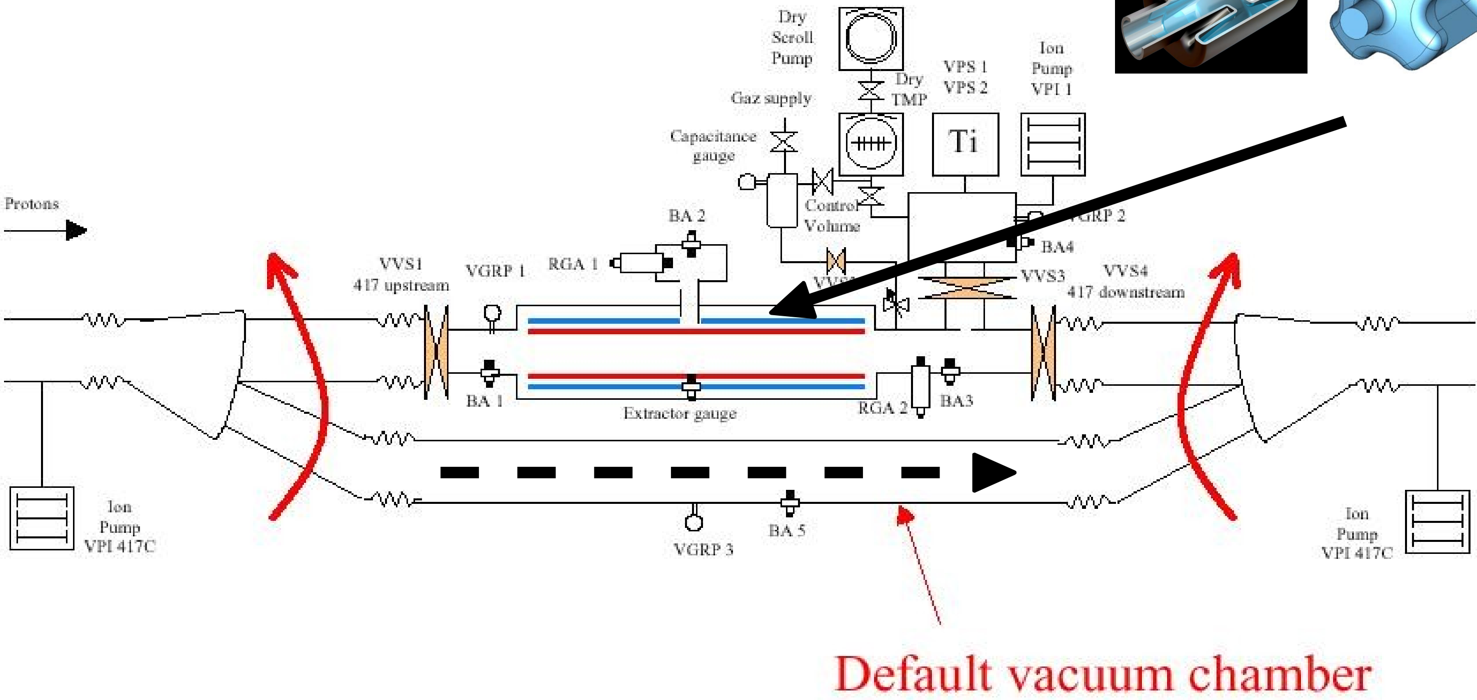


SPS As a Testbed







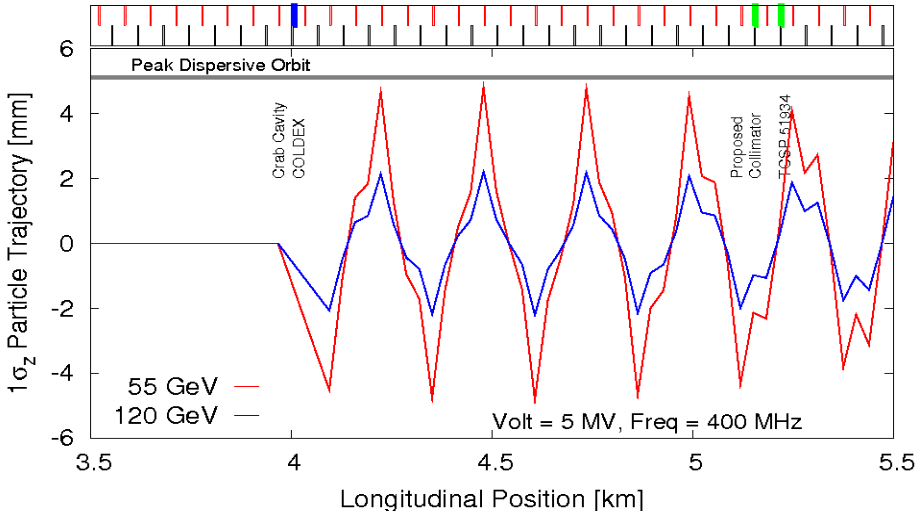


Long. Position: 4009 m +/- 5m

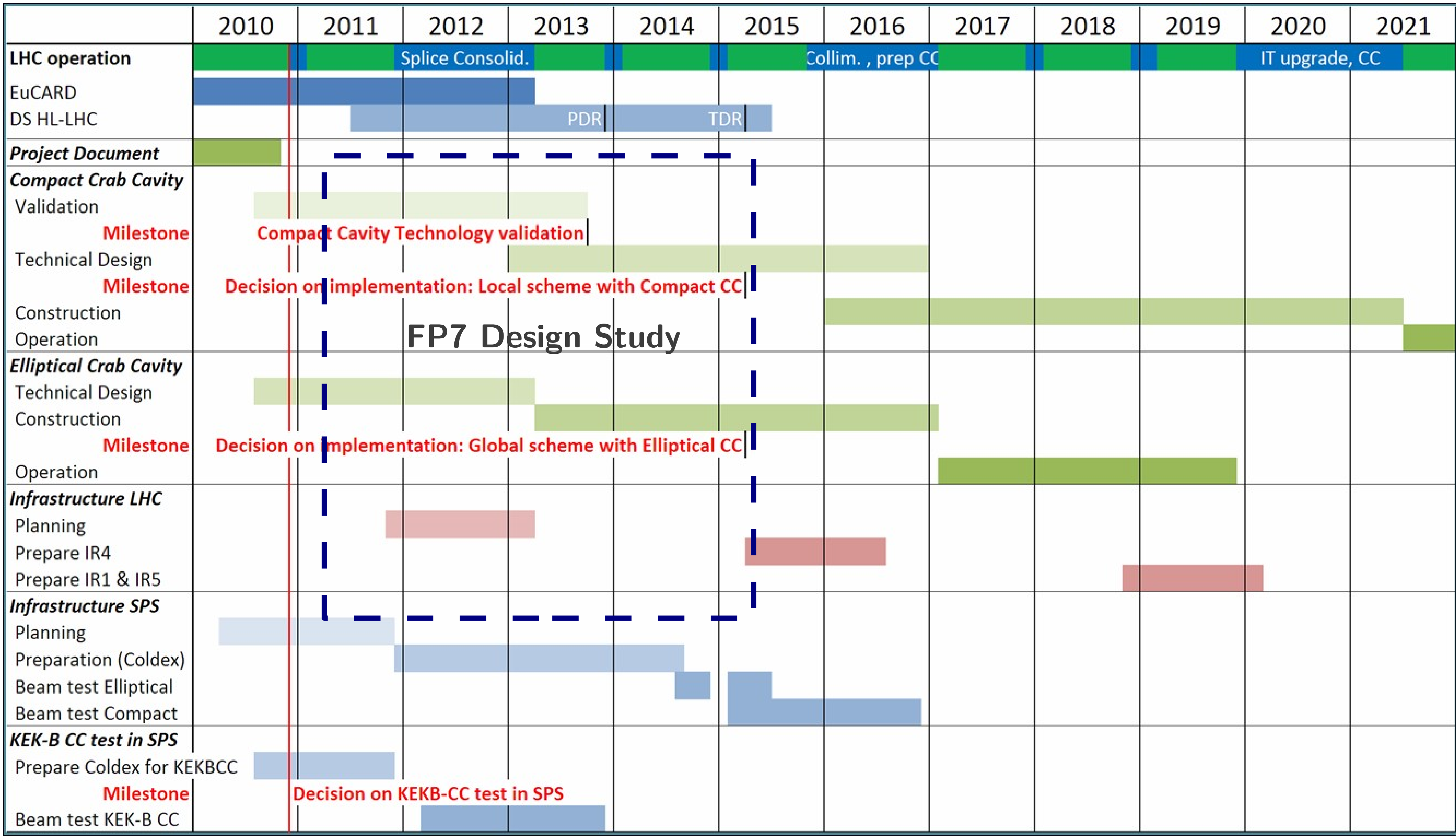
Total length: 10.72 m

βx, βy: 30.3m, 76.8m

Emittance growth, cavity operation & failures with hadron beam



Overall Planning



Budget Overview

Material Budget

MCHF	2011	2012	2013	2014	2015	2016	2017-20
R&D (3-4 cavities)	3.55	5.6	3.4	2.35	3.3	1.15	0.1
Cavity Construction						3.5	17.5
Cryostats						4.0	30
RF Systems						1.0	6.5
LLRF & Controls						0.3	5

10 cryomodules + Ancilliaries **Total: 87.25 MCHF**

Present support (R&D):

US-LARP ($0.4M/yr), EU-FP7 (~1.5M€/yr), SBIR/STTR ($1.25M)

Future & Challenges

Fabrication

Complex shapes, but this community already has experience

Build warm prototypes to gain experience & HOM measurements

Cavity treatment

Independent platform for each prototype but common procedure

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

Cryostat & Couplers

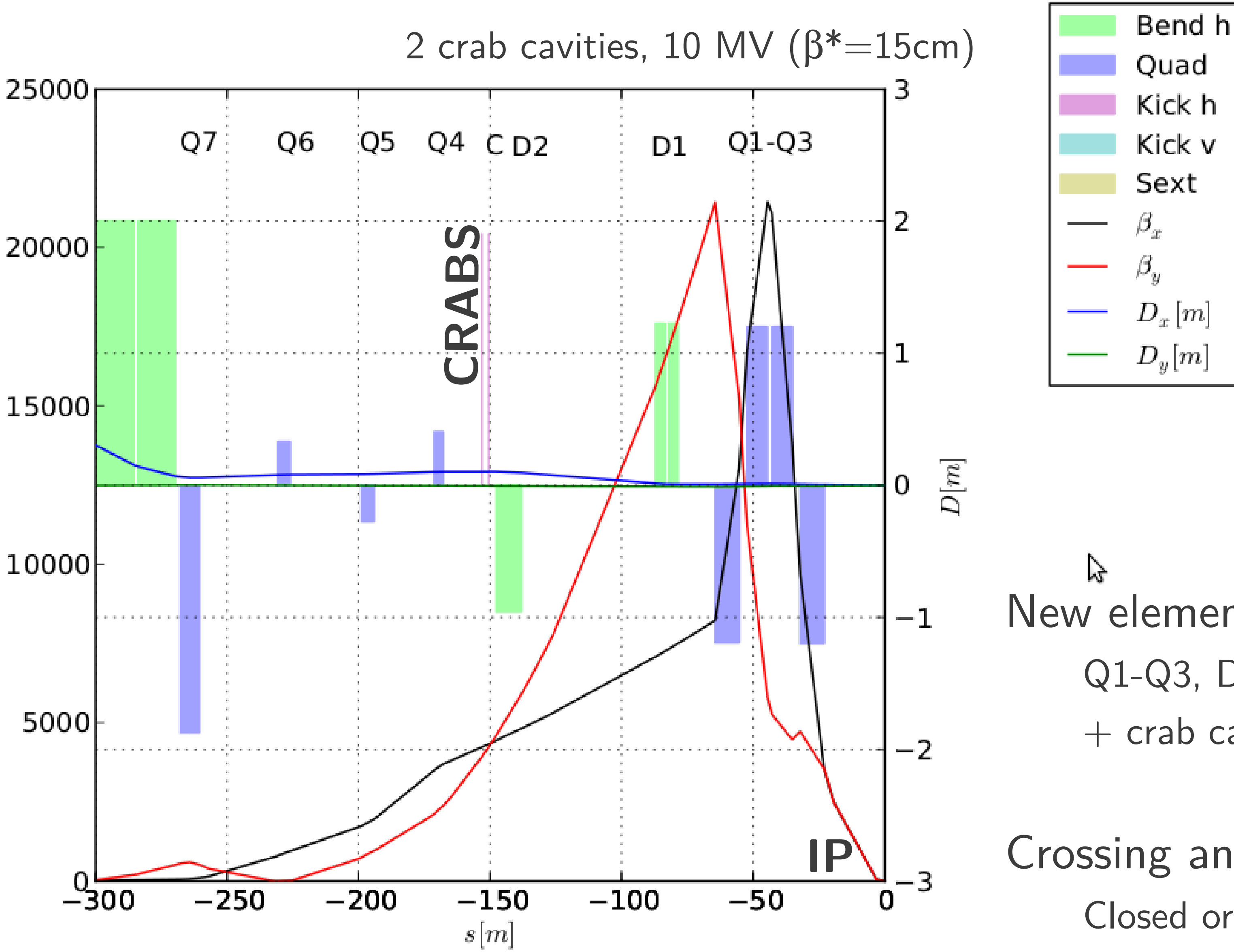
Adopt a common platform (after prototyping), for example could use bandpass filter for the HOM extraction

RF & Beam tests

Cavity deflecting gradient, multipacting and quench properties with and w/o beam, field assymetry, cavity alignment, impedance measurements, damping properties, mechanical stability, tuning, emittance growth, field ramping, RF controls, phase and voltage stability etc..

A1: Draft Optics (SLHC v3)

S. Fartoukh, R. deMaria



New elements (SLHC v3)

- Q1-Q3, D1, TAN, D2, Q4-Q5
- + crab cavities (~10 m, 10 MV)

Crossing angle change

- Closed orbit excursion (~3 mm)
- Remote cavity alignment