Fermilab

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Power Couplers, HOM couplers and Beamline absorbers

Nikolay Solyak
SRF workshop, Round Table discussion
10 February 2017

HEP road map in ~10 years time scale

- **High Energy Frontier projects**
  - ILC (SC), TeV - scale with staging scenario: Higgs factory
  - FCC, lepton options (Z,W,H,t); ep and hh collider - 100TeV
  - NC linear collider (CLIC) – up to 3TeV

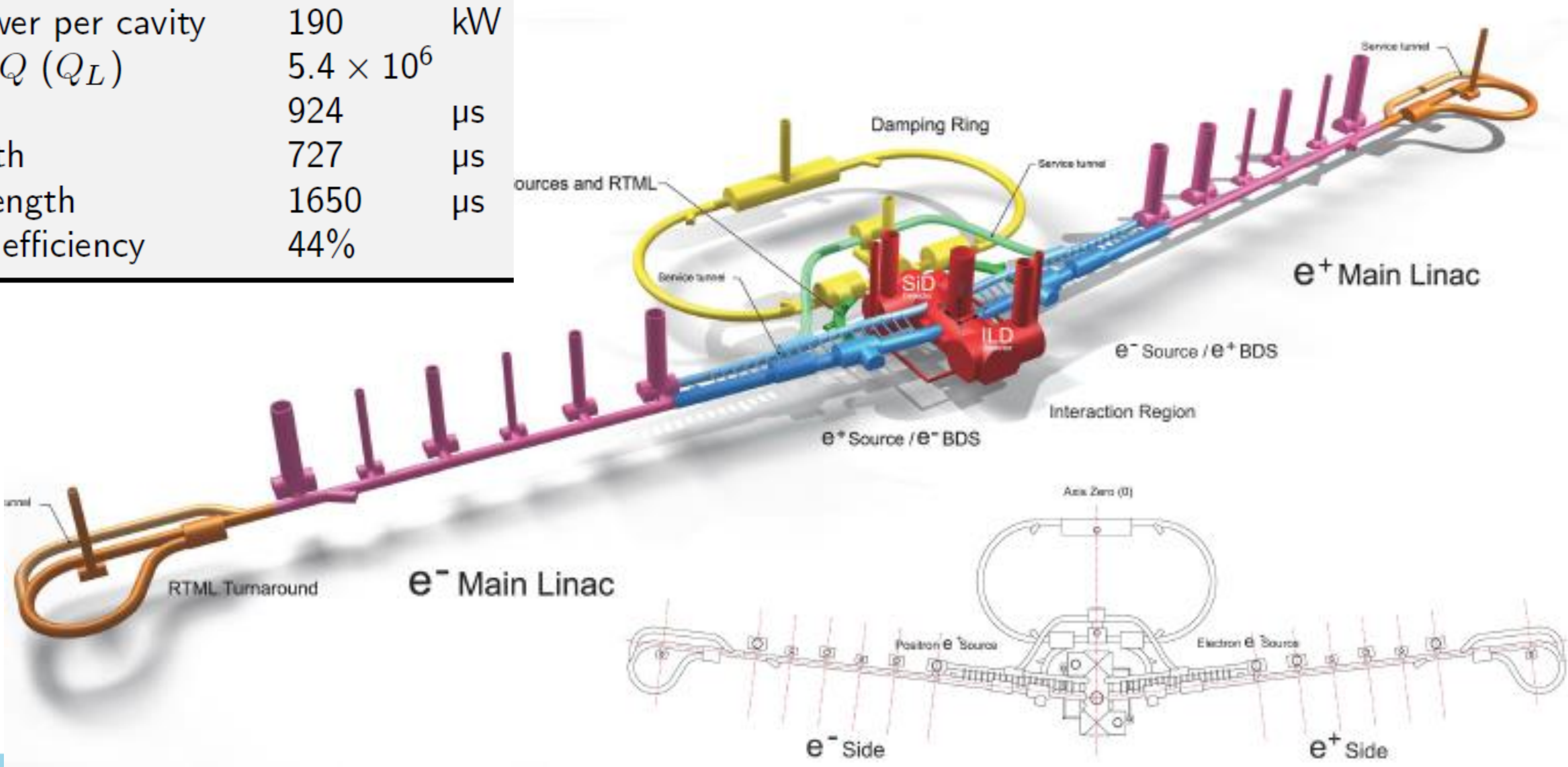
- **Intensity Frontier projects**
  - High Power proton linacs (PIP-II, upgrades) and circular accelerators for production of multi-MW beams for precise measurements in
    - Neutrino physics
    - Kaon, Muon, …physics

Future HEP accelerators will be mostly based on SRF technology

ILC (TDR)

Centre-of-mass energy	E_{CM}	GeV	200	230	250	350	500
Luminosity pulse rep.rate		Hz	5	5	5	5	5
Positron production mode			10 Hz	10 Hz	10 Hz	nom.	nom.
Estimated AC power	P_{AC}	MW	114	119	122	121	163
Bunch population	N	$\times 10^{10}$	2	2	2	2	2
Number of bunches	n_b		1312	1312	1312	1312	1312
Linac bunch interval	Δt_b	ns	554	554	554	554	554
Luminosity	L	$\times 10^{34}$ cm^{-2} s^{-1}	0.56	0.67	0.75	1.0	1.8

RF requirements (for average gradient)		
Beam current	5.8	mA
beam (peak) power per cavity	190	kW
Matched loaded Q (Q_L)	5.4×10^6	
Cavity fill time	924	µs
Beam pulse length	727	µs
Total RF pulse length	1650	µs
RF–beam power efficiency	44%	



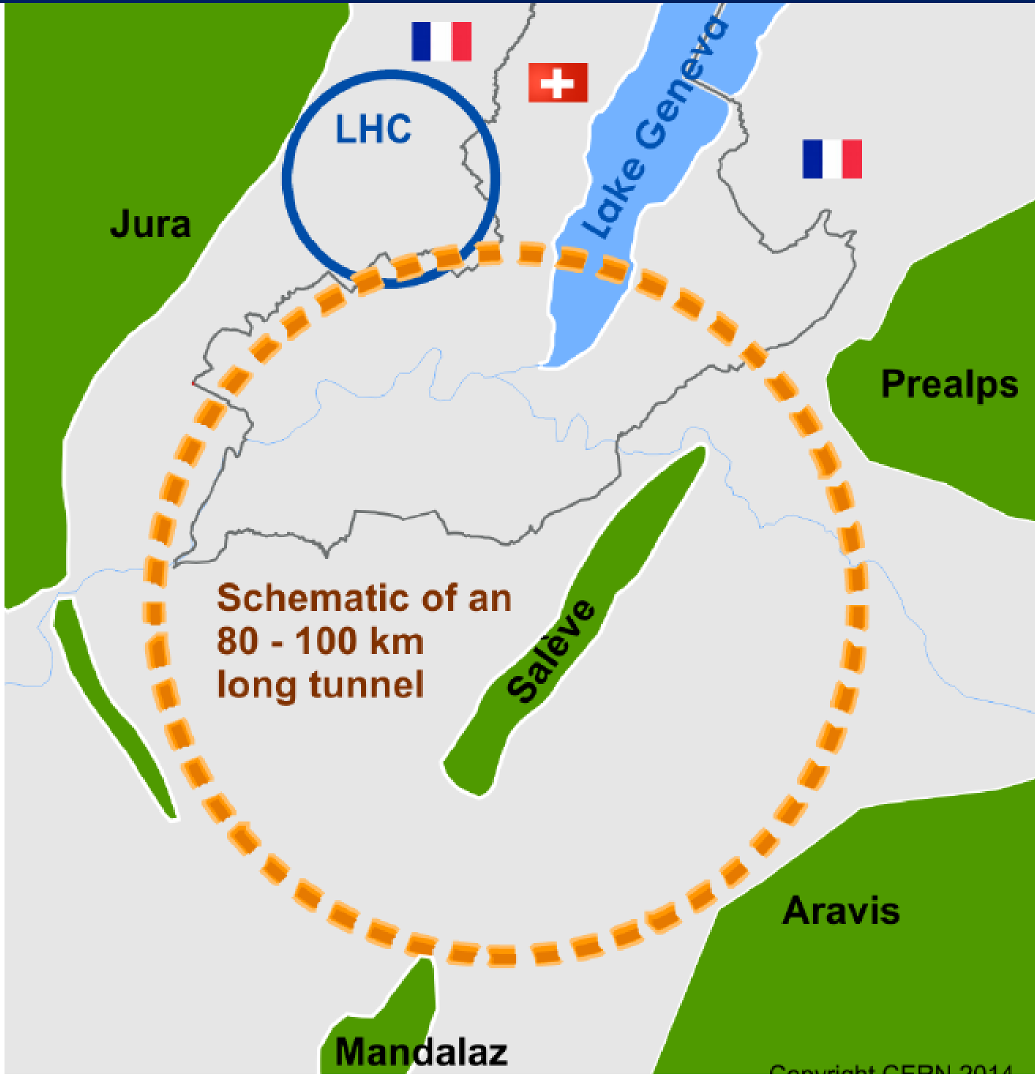
Future Circular Collider Study - SCOPE
CDR and cost review for the next ESU (2018)

Forming an international collaboration to study:

- ***pp*-collider (*FCC-hh*)**
  → defining infrastructure requirements

~16 T ⇒ 100 TeV *pp* in 100 km
~20 T ⇒ 100 TeV *pp* in 80 km

- **e^+e^- collider (*FCC-ee*)** as potential intermediate step
- ***p-e* (*FCC-he*) option**
- **80-100 km infrastructure** in Geneva area



RF system requirements

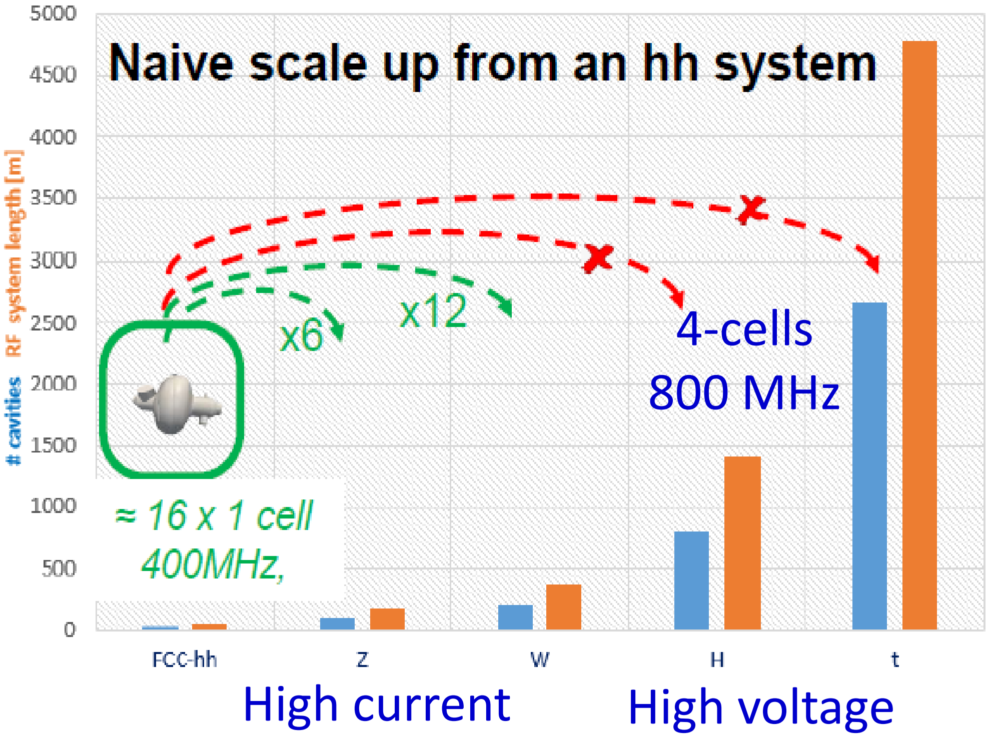
Very large range of operation parameters

“Ampere-class” machines

	V_{total} GV	$n_{bunches}$	I_{beam} mA	ΔE/turn GeV
hh	0.032		**500**	
Z	0.4/0.2	30000/90000	**1450**	0.034
W	0.8	5162	152	0.33
H	**5.5**	770	30	1.67
t	**10**	78	6.6	7.55

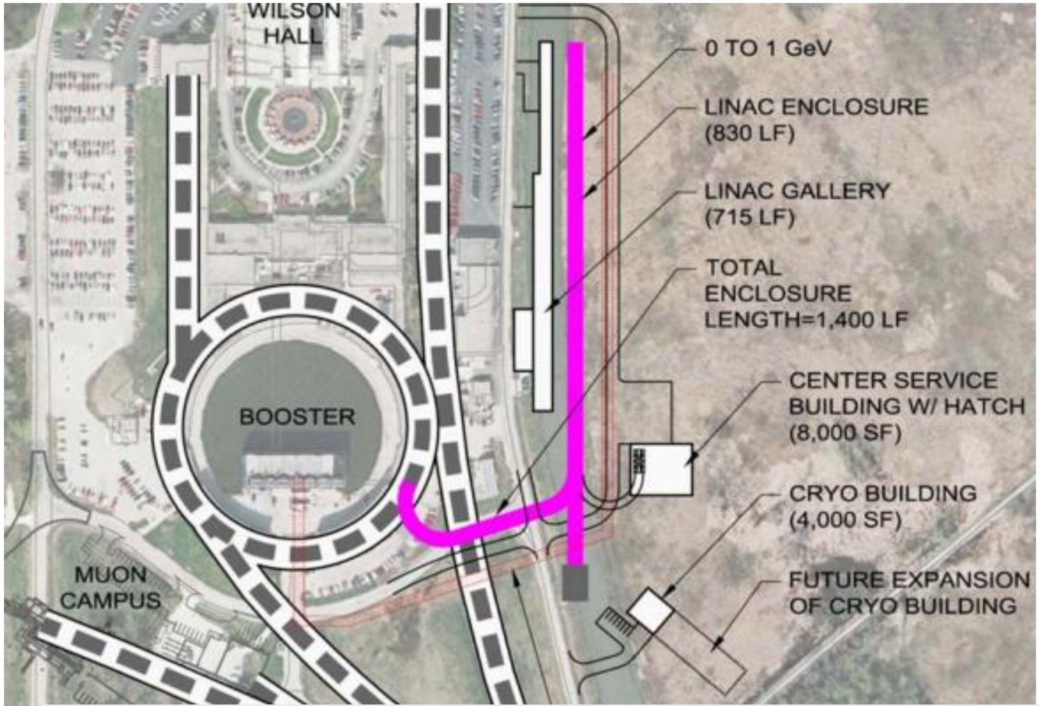
“high gradient” machines

Synchrotron power = 50MW/beam



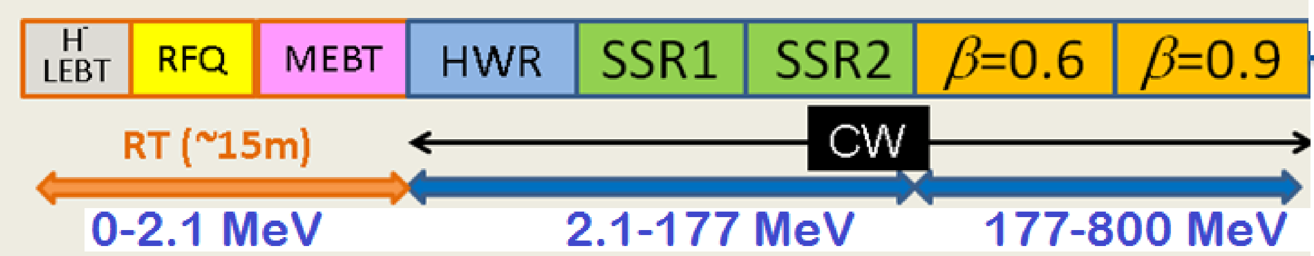
- **Voltage and beam current ranges span more than factor > 10^2**
- **No well-adapted single RF system solution satisfying requirements**

PIP-II Linac Requirements:



Linac Beam Energy	800	MeV
Linac Beam Current	2	mA
Linac Beam Pulse	0.6	msec
Linac Pulse Rep.Rate	15	Hz
Linac Upgrade Potential	CW	

- Low beam loading;
- Long filling time compared to pulse length;
- Low efficiency at pulse mode.



→ To the booster

Possible upgrades: 5mA; cw regime; extend to 8GeV (PIP-III)

Fundamental power coupler requirements:

FCC-ee

- Freq: 400 & 800 MHz
- Power up to 500 kW cw (Z, W mode);
- QL ~ 1.e6 – 5.e6; tunable coupler is desired

ILC (incl. upgrade options)

- Freq: 1.3GHz (2.6GHz); 1.65ms x 10 Hz
- Power: up to 80MVx6mA~0.5 MW (pulse, SW); average power ~10 kW

Intensity frontier (PIP-II; upgrades: 5mA, cw, high energy)

- Freq: 162.5; 325; 650 and 1300 MHz
- Power: ~100 kW; cw

Other requirements:

- Low cryogenic load (2K,5K,50K)
- Cleanable, tunable or fix coupling
- Advance Materials (ceramics) and technology (brazing, Cu plating, coating)
- Relatively cheap in production
- Low Cost

Synergy is essential key for design strategy

Power coupler issues:

- High peak and average power (~kW to MW)
  - *Cooling and overheating problems*
  - *Heat loads to cryogenic system*
  - *Multipacting, MP suppression (bias) and diagnostics,*
- Materials: ceramics-losses and therma, non-magnetic materials.
- Technology (many critical technologies: copper plating, TiN coating, brazing/welding,
- QC/QA on vendor site: (RRR, thickness, cleaning, baking…)
- HP processing (test stands, protocol, MP etc)
- Reproducibility
- **Cost. Reliability and Performance**

Coupler Cost

- Currently is expensive and critical component of SRF system
- QC/QC need to be improved
  - Cost ~ 30% of dressed cavity (XFEL, LCLS-II)
  - Raw materials cost ~20-25%;
  - Copper plating and ceramics coating ~ 40%
  - Brazing ~ 20%

Direction on coupler R&D:

- Design: geometry with reduced MP threshold (DC bias)
- minimize heating and cryoloads (Air/N/He cooling)
- Simple WG box (LCLS-II Aluminum box, no welding/brasing)
- No copper plating
- no TiN coating (Ceramics with low SEY)
- Work with industry on technology and QA/QC

A-3. Power input coupler fabrication

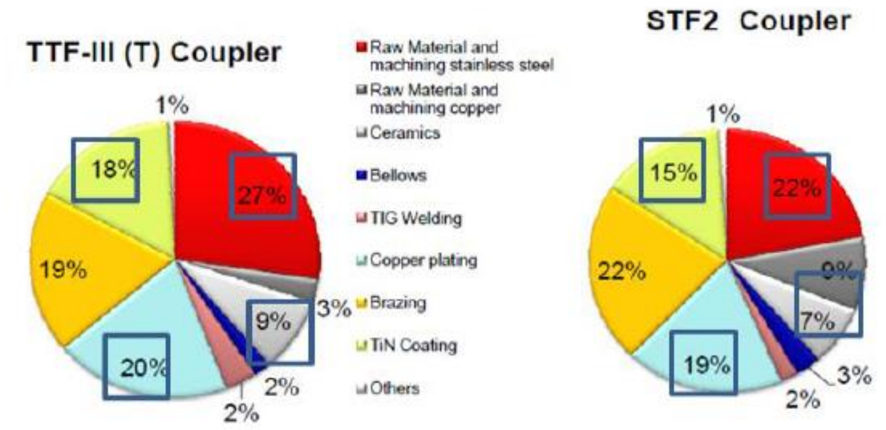
- By innovating the ceramic window material, we will try to make the coupler without additional surface treatment on the ceramic leading to the cost reduction.

- Material cost (including Cu plating) in cavity input coupler is rather high. We will review the materials and Cu plating procedure.

STF-2 Couper

TTF-III Couper

Cost Estimate of TTF-III and STF2



TTF-III (T) : Toshiba modifying version

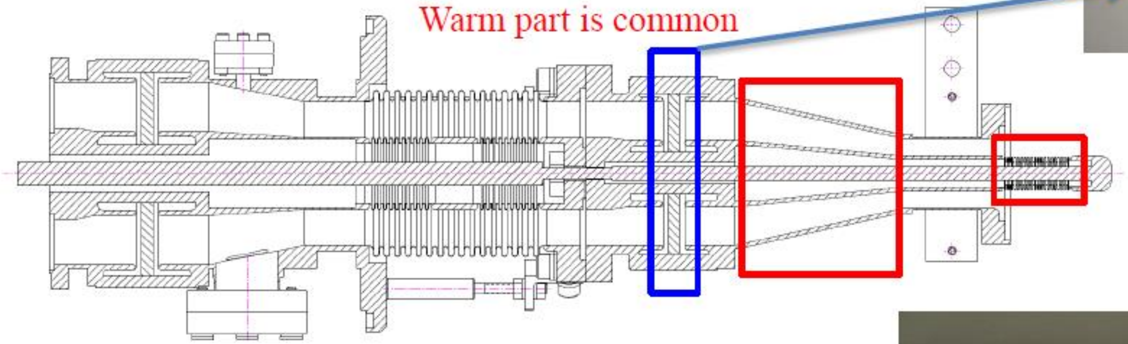
Schedule

	2016	2017	2018	2019
KEK E. Kako Y. Yamamoto	Evauation of ceramic (on going)	Design Collaboration with FNAL	Manufacturing High power test	#2 Manufacturing High power test Manufacturing For cyromodule

New Ceramics: DC conductivity and low SEY (no TiN coating)

KEK STF-type Coupler RF Design & Fabrication

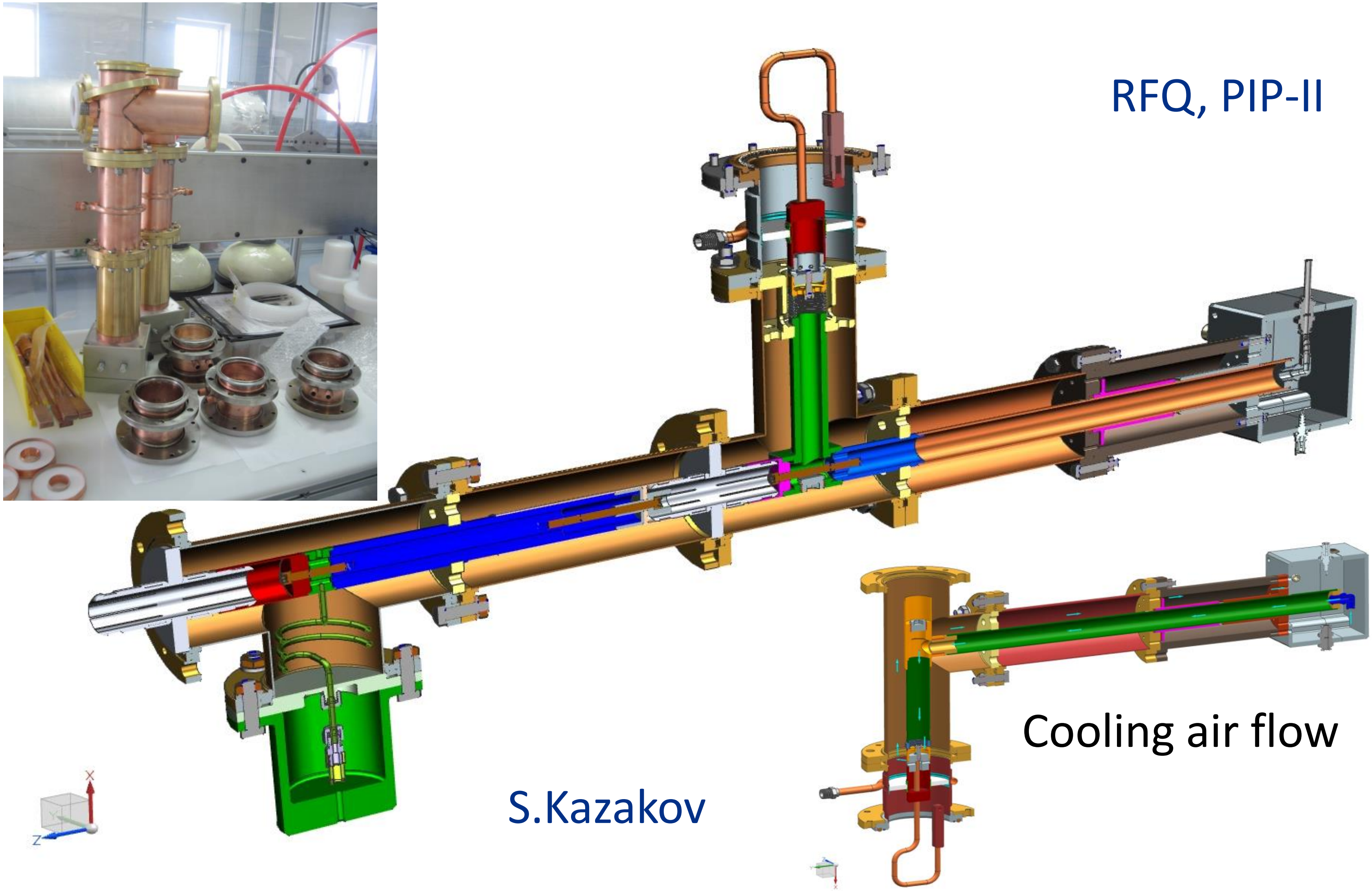
Coupler (TOSHIBA)	Product No.	Serial No.	Ceramic company	Ceramic color	Ceramic coating
Warm #1, #2 (normal)	E42130	14L001 14L002	NGK/NTK	White	TiN
Cold #1, #2 (normal)	E42130	14L001 14L002	NGK/NTK	White	TiN
Cold #3, #4 (new)	E42130	14L003 14L004	KYOCERA	Gray	free



Shin Michizono, KEK

- View point of plug-compatibility
  - Longer tapered pipe for 40mm port
  - Longer bellows for wider range of Q_L
- View point of lower cost study
  - Coating-free ceramic
    - Coating process is dominant in cost

162.5 MHz, 100 kW, CW RFQ Power Coupler

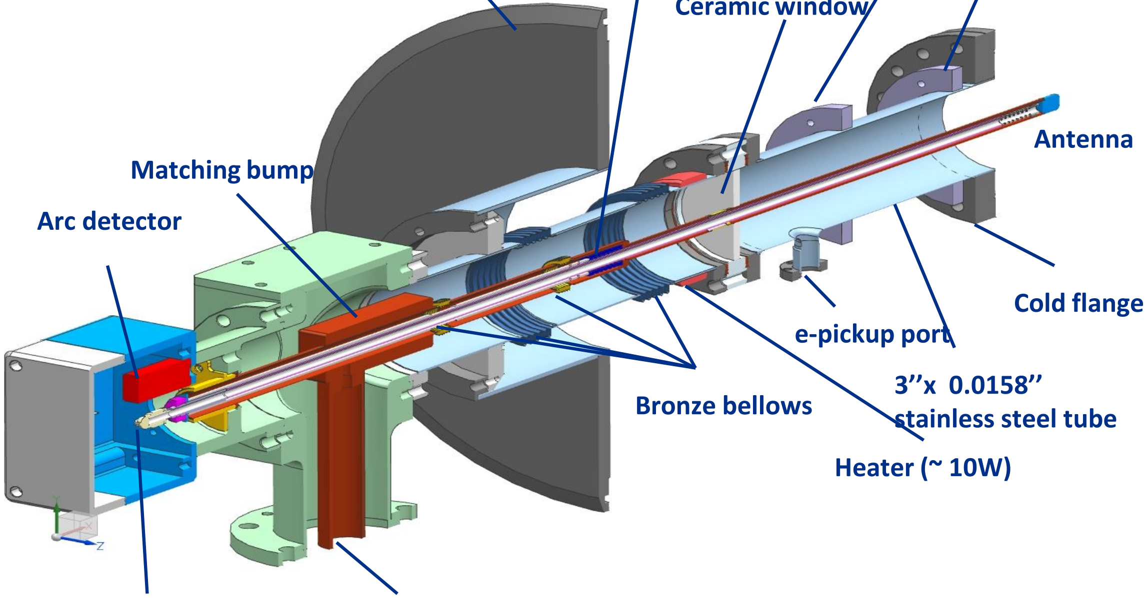


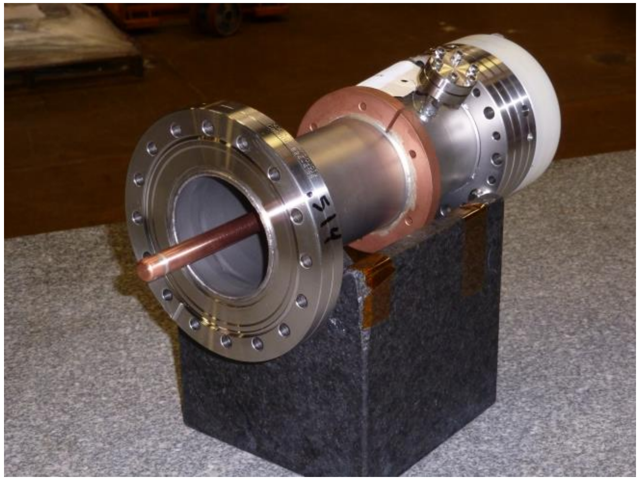
RFQ, PIP-II

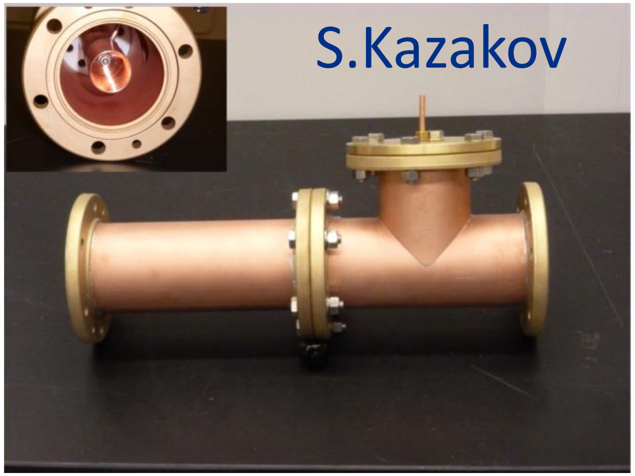
Cooling air flow

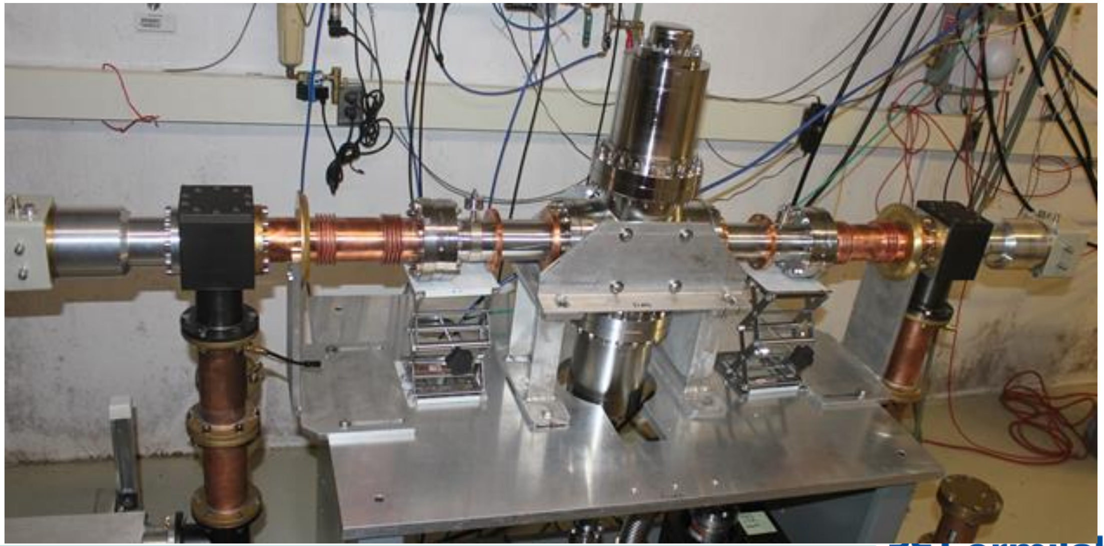
S.Kazakov

325 MHz coupler
30kW cw

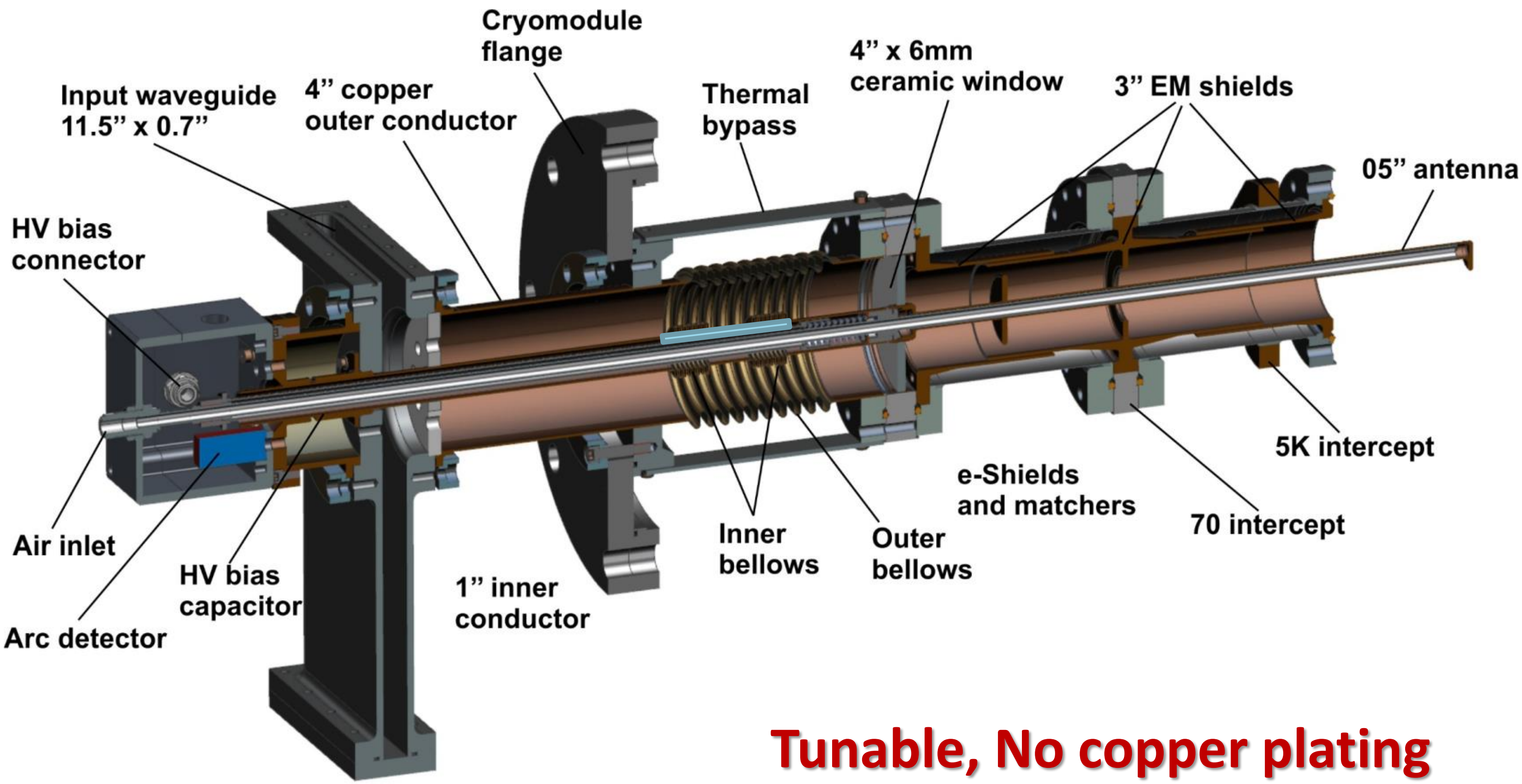

Cryomodule flange
Spring to compensate thermal expansion
"5K" intercept
"80K" intercept
Ceramic window
Antenna
Matching bump
Arc detector
Cold flange
e-pickup port
Bronze bellows
3''x 0.0158'' stainless steel tube
Heater (~ 10W)
Air inlet
3-1/8'' coaxial input




S.Kazakov



Structure of 650 MHz coupler (PIP-II design)



Tunable, No copper plating

Power 120 kW CW, pulse 3MW

Air cooling of central conductor

HV bias for MP suppression

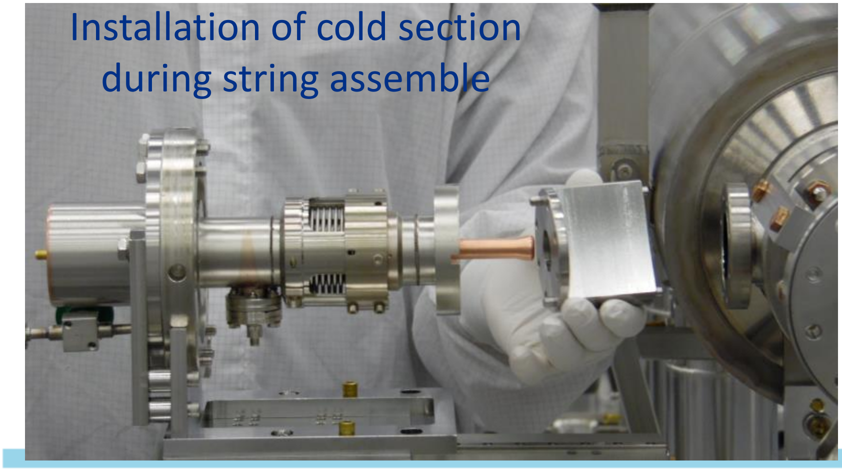
ILC baseline coupler (Limited in power, pulsed and average)

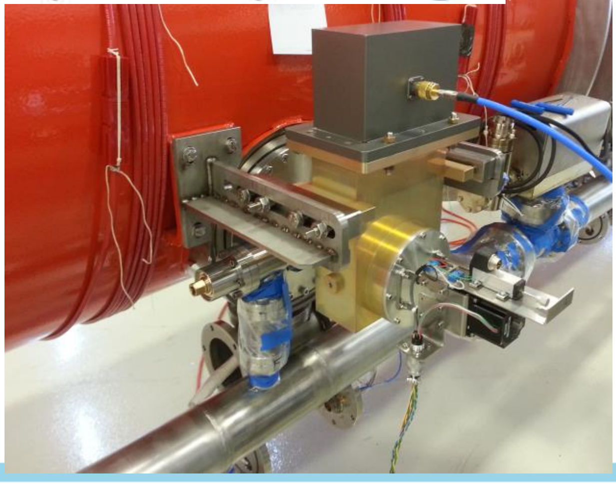
Copper plating increased to 150µm for Pav ~ 6kW (LCLS-II)


Pair of cold assemblies


Warm assembly


Assembling warm and cold pair for RF processing


Installation of cold section during string assemble



Photos courtesy J. Tice

Short-term R&D (2-3 years) milestones for ILC coupler

- Optimize the XFEL/LCLS-II coupler design (collaboration with SLAC) for high peak and average power. Build two prototypes of the coupler, develop a test stand for high power evaluation. Perform measurements of the new ceramics (collaboration with KEK.
- Commission the test stand and test two couplers. Perform further modifications /improvements of the design, order second pair of couplers for the high-*Q*, high-gradient cavity in the cryostat.

Medium-term R&D (4-5 years) milestones

- Develop new coupler design, fabricate and test prototypes.
- Build CM with high-*Q* / high-gradient / new-shape cavities and cost-reduced couplers: demonstrate 40-45 MV/m in CM with additional cost reduction avenues for total cost savings up to 25%.

Long-term R&D (10 years) for ILC HE upgrade milestones

- Develop cost effective coupler for cavity with ~80MV/m; using advance technology, no copper plating, new ceramics. Build and test prototypes.
- High-*Q* / high-gradient CM test (with beam) at FNAL or at KEK.

HOM Damping: Approaches, concepts

New SRF accelerators put high demands on the HOM damping schemes (high power, broadband…)

- SRF systems of the future energy frontier *e+e-* linear and circular collider (CEPC and FCC) will have to deal with high average current particle beams consisting of a large number of short bunches, wideband spectra with densely spaced frequency lines. Therefore HOM damping schemes for future colliders are quite challenging. Any selected scheme will have to be capable of handling kilowatts of HOM power via a combination of HOM couplers and beam pipe absorbers.
- High intensity frontier accelerators: low current and sparse beam spectrum → relaxed requirement for HOM damping

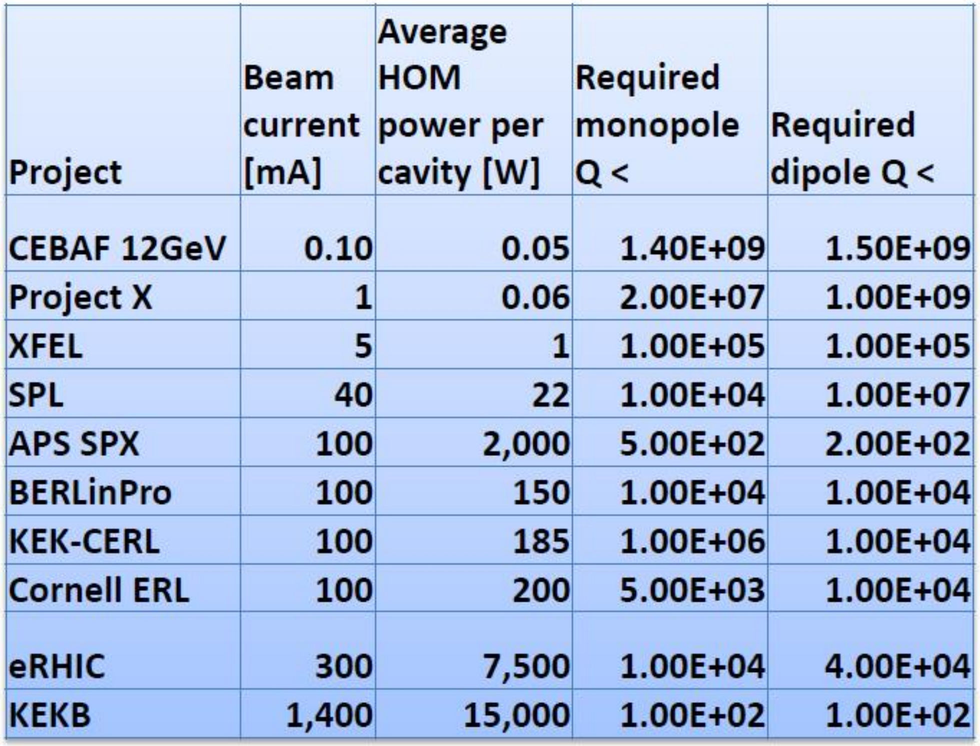
HOM damping challenges for high intensity accelerators (example: FCC-ee)

- Effectively handle high HOM power up to 10 kW/cavity
- Provide strong HOM suppression Q~10^2-10^5
- Broadband (~100GHz)
- Inexpensive, not occupy beamline length

Fortunately not all in the same time.

Different requirements → different solutions

Beam Current and HOM Damping Requirements



Project	Beam current [mA]	Average HOM power per cavity [W]	Required monopole Q <	Required dipole Q <
CEBAF 12GeV	0.10	0.05	1.40E+09	1.50E+09
Project X	1	0.06	2.00E+07	1.00E+09
XFEL	5	1	1.00E+05	1.00E+05
SPL	40	22	1.00E+04	1.00E+07
APS SPX	100	2,000	5.00E+02	2.00E+02
BERLinPro	100	150	1.00E+04	1.00E+04
KEK-CERL	100	185	1.00E+06	1.00E+04
Cornell ERL	100	200	5.00E+03	1.00E+04
eRHIC	300	7,500	1.00E+04	4.00E+04
KEKB	1,400	15,000	1.00E+02	1.00E+02

- High beam current requires high power handling capabilities of HOM damping scheme

$$P_{avg} = k_{||}QI$$

- Risk of resonant mode excitation and beam stability **require strong HOM damping by HOM damping scheme**

Types of HOM high power absorbers, performance

- **Beamline Absorbers**

  Pros: Broad band, high power (~10kW at RT, ~100W at cryotemp), damp all polarizations

  Cons: Absorbing materials; cavity contamination, extra HOM generation, longitudinal space

- **Waveguide HOM dampers**

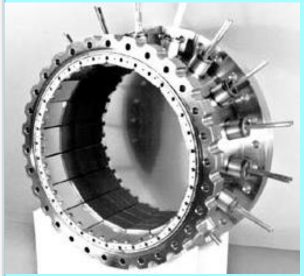
  Pros: Broad band, compact, high power (kW), can be at RT

  Cons: complex cavity and CM design

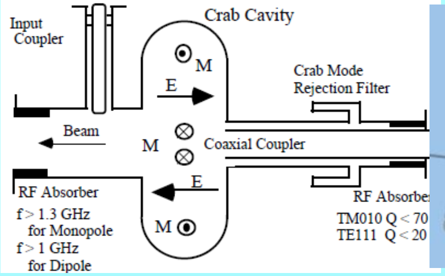
- **Loop/antenna HOM couplers to a coaxial line (HERA, LEP, LHC)**

  Pros: Broad band, easy to clean, power ~1kW

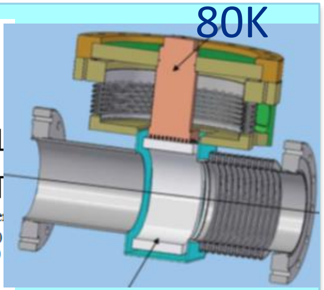
  Cons: filter to reject fundamental mode, one polarization



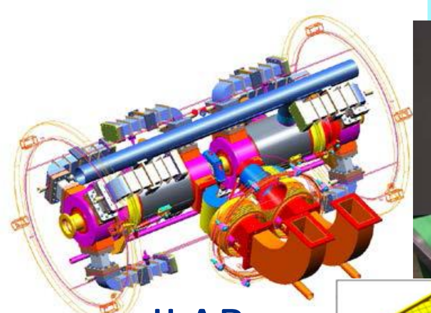
CESR



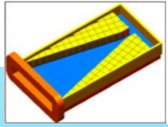
KEKB-crab cavity



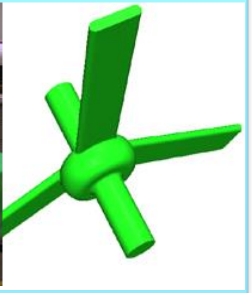
XFEL/ILC



JLAB

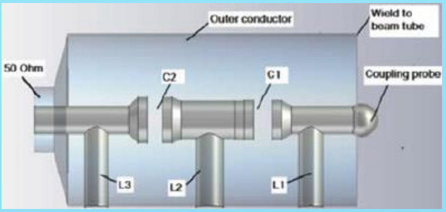


750MHz-ERL

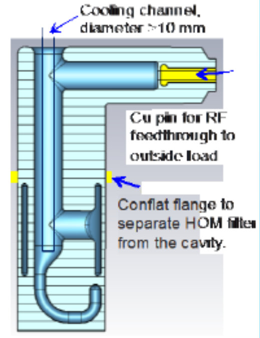


MEIC

LHC HOM couplers narrow/broad band



BNL3704MHz cav. HOM coupler 2-step band stop filter

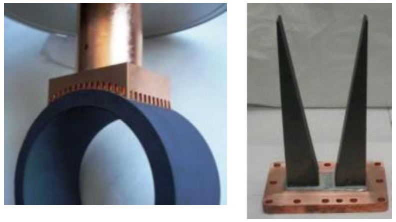


HOM coupler of crab-QWR: HL-LHC.

RF absorbing materials

Requirements: good losses in broad band (up to 100’s GHz), UHV, DC conductivity; good thermal conductivity; cleanable, brazeble, low SEY, reproducible in production, etc.

- **Ferrite:**
  - Very lossy; T-dependent; not broadband, brittle, low CD conductivity



- **Ceralloy CA137**
  - Broadband; lossy; good DC conductivity; poor reproducibility in production

- **Graphite loaded SiC**
  - Broadband; Temp dependent, less lossy
- **Carbon-Nanotube loaded Alumina Ceramics**
  - Quite lossy and broadband; Temp independent, Sufficient DC conductivity at 300K and 80K; Currently only available in small samples; Still in R&D phase