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TTC2014, 24th March, 2014 DESY

Limits for peak fields and gradient in low-beta cavities for high intensity projects

Yuan He

Linac Center

Institute of Modern Physics

Chinese Academy of Sciences

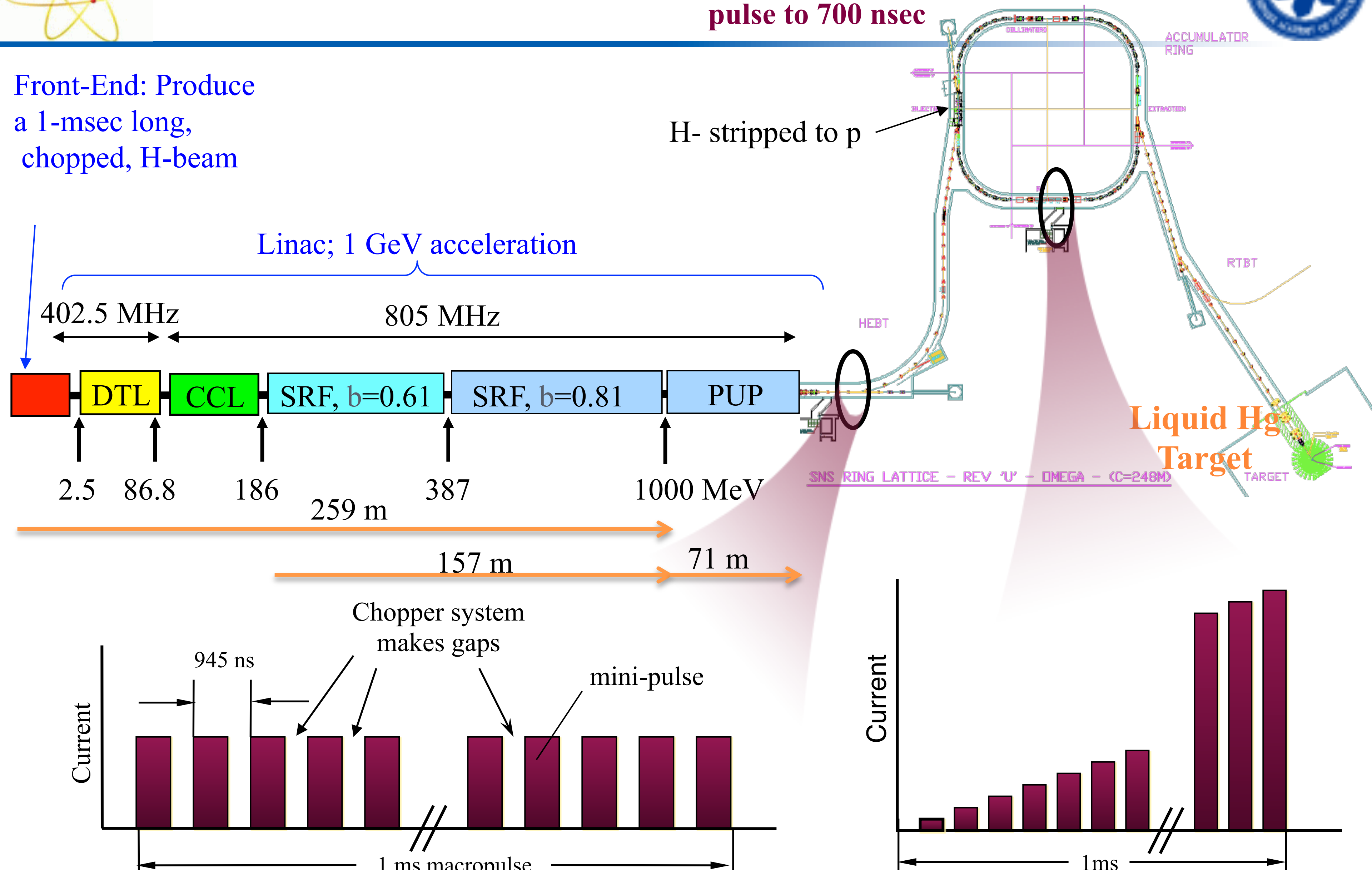
Overview of SC Cavities in the High Intensity Projects

		SNS	SARAF	Spiral2	FRIB	China ADS	PIP II	IFMIF	ESS	MYRRHA
Cavity	HWR		√		√	√	√	√		
	QWR			√	√					
	CH									√
	Spoke					√	√		√	√
	Elliptical	√				√	√		√	√
Beta Range		0.61, 0.81	0.09 0.15	0.07, 0.12	0.04, 0.085 0.29,0.53	0.09-0.85	0.1-0.9	0.1 0.15	0.5-0.9	0.06-0.65
Particle	proton	√	√			√	√		√	√
	Deuteron		√	√				√		
	Heavy ion			√	√					
Beam Mode	CW		0.04-5mA	5mA (D), 1mA (Heavy Ion)	~1mA	10mA	2 mA	125mA		4mA
	Pulse	60Hz, 0.65ms, peak 30mA					15Hz, 0.6ms, 2mA		14Hz, 2.86ms, peak 62.5mA	

SNS Machine layout

Accumulator Ring: Compress 1 msec long pulse to 700 nsec

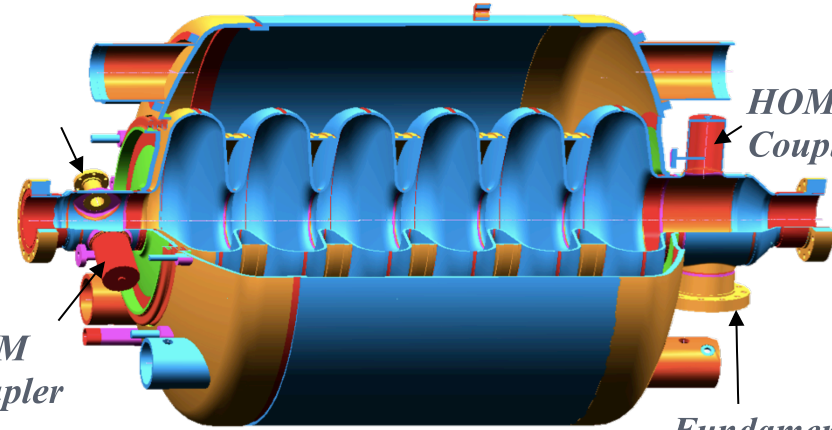
By Sang-Ho Kim

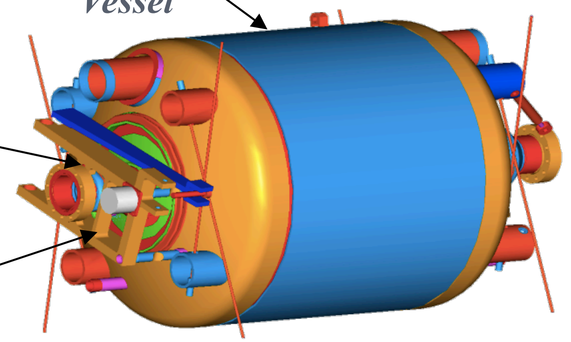


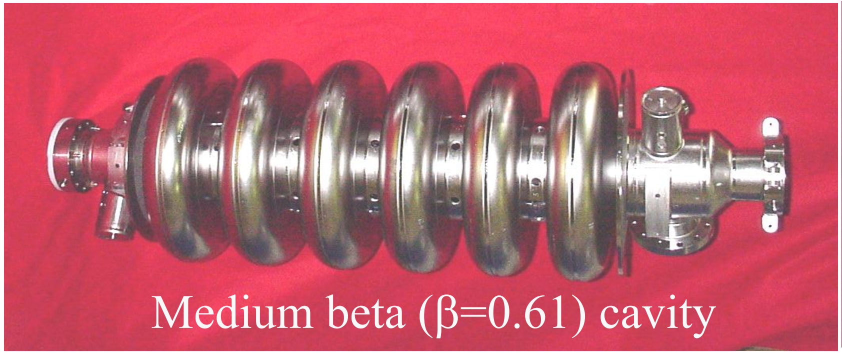
SNS SRF Cavity

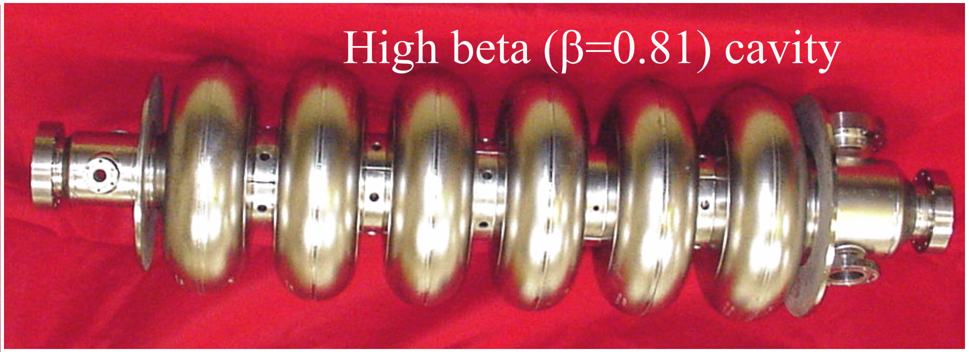
By Sang-Ho Kim

Major Specifications:
E_a=15.8 MV/m at β=0.81
E_a=10.2 MV/m at β=0.61
&
Q_o> 5e10^9 at 2.1 K

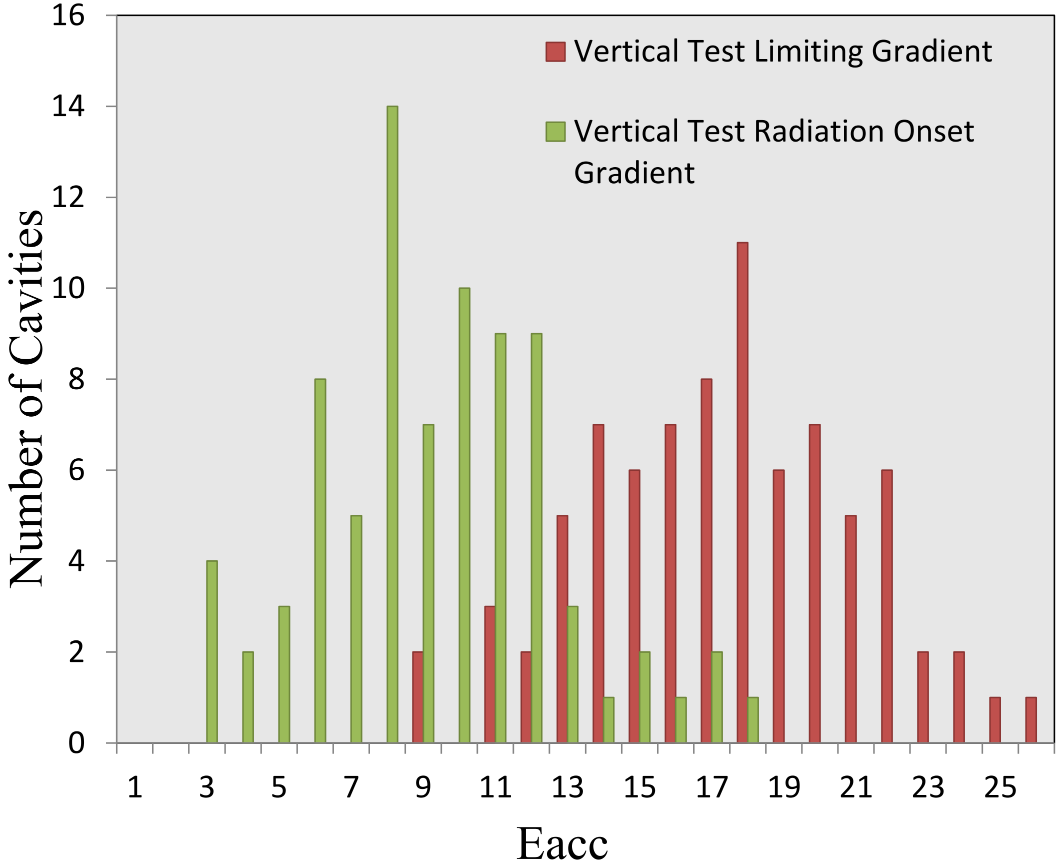


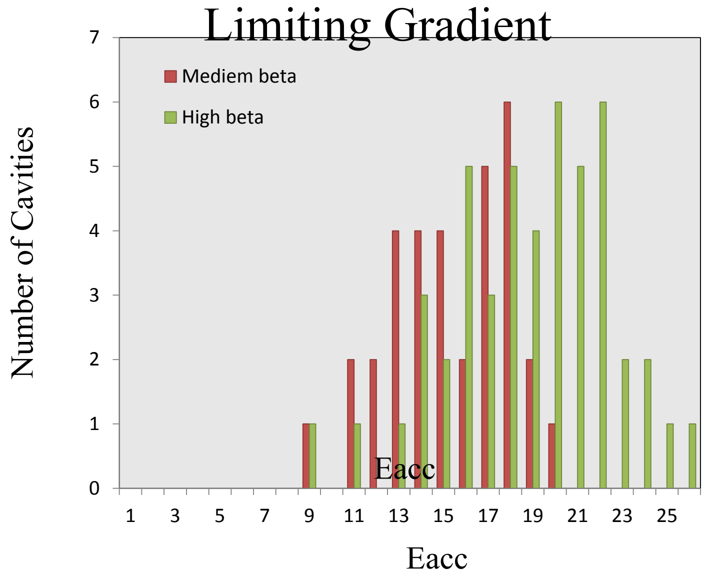


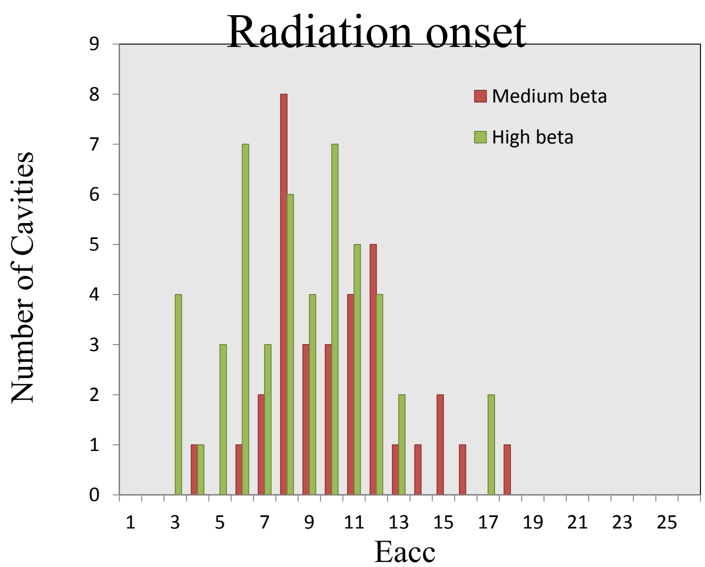




VTA Test Statistics







By Sang-Ho Kim

Cryomodule test (individually powered at 10 Hz, 1.3 ms RF in open loop)

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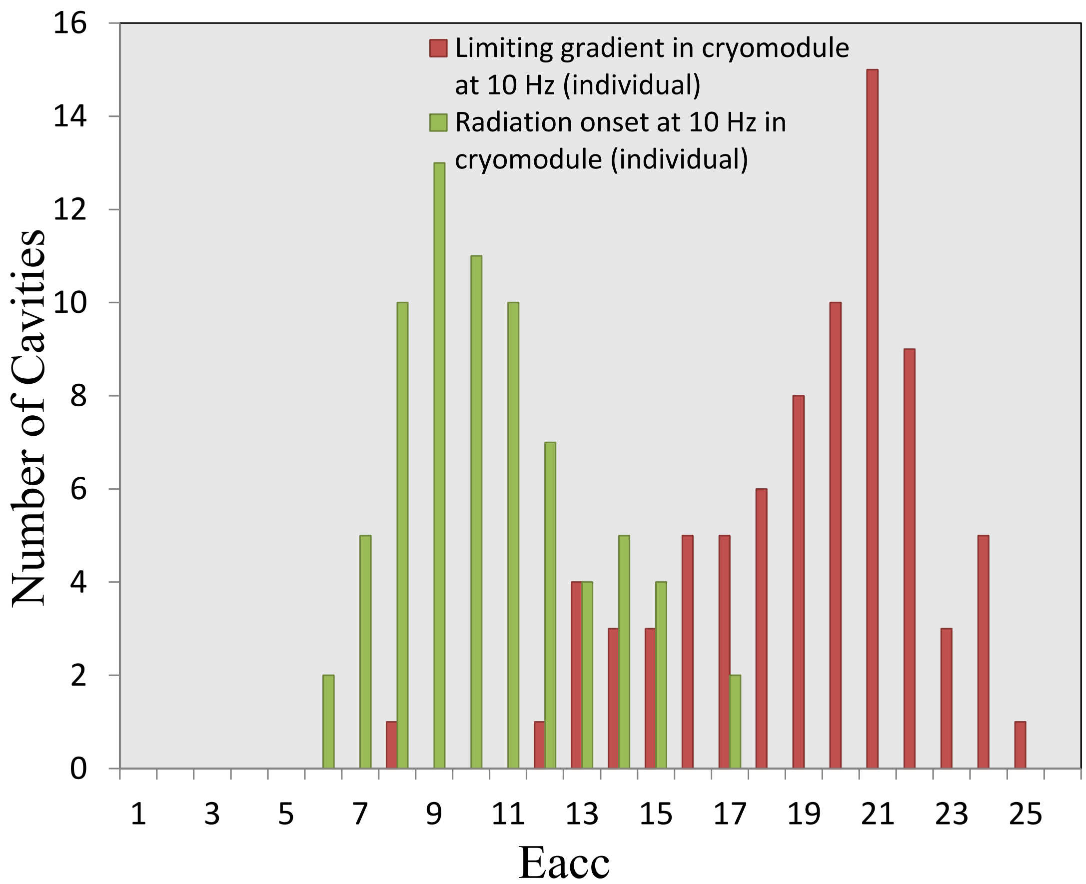
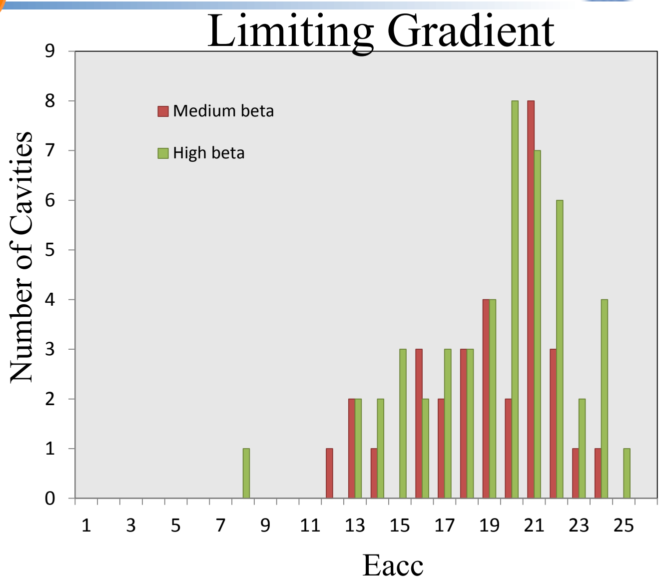
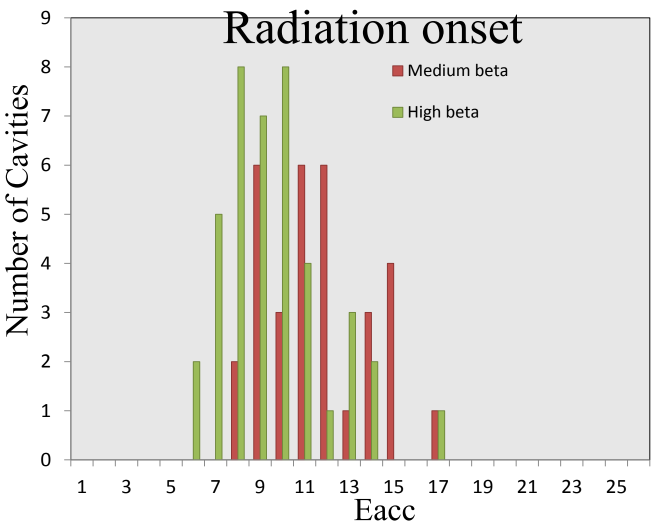




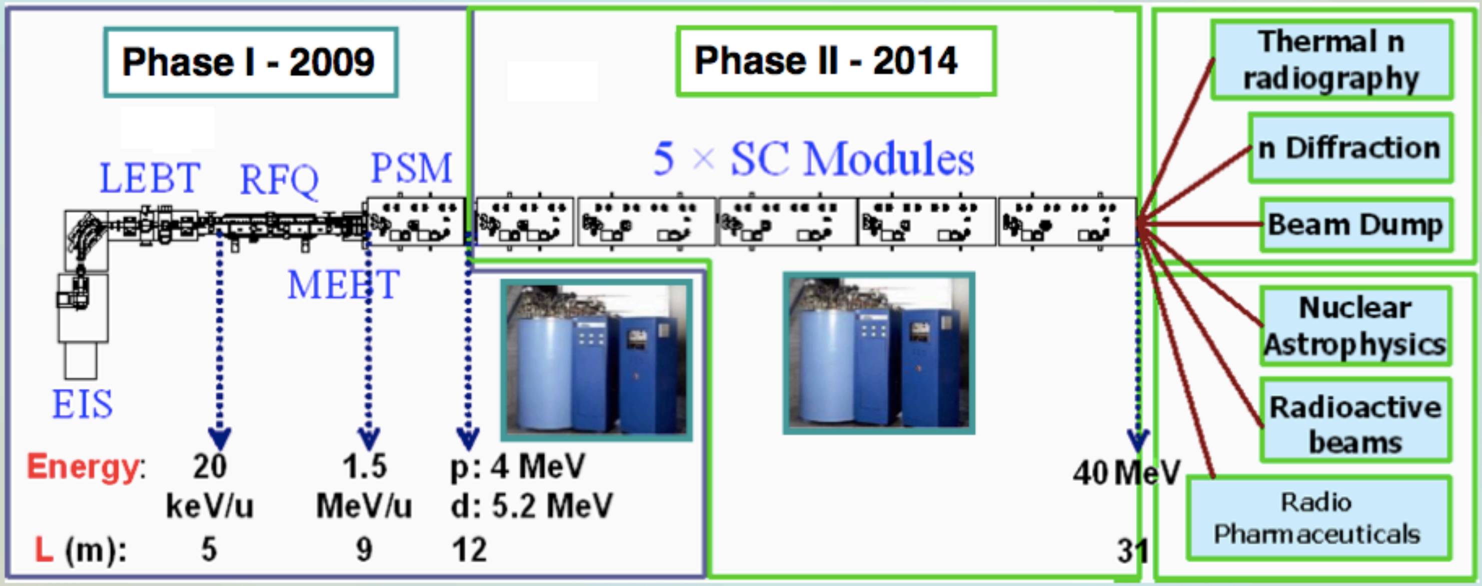


- Lack of correlation between VTA test and Cryomodule test: additional processing after the VTA testing, yielding two different cavity surfaces.

Layout of SARAF

Soreq Applied Research Accelerator Facility

RF Superconducting Linear Accelerator | **Target Hall**



Current Range	0.04 – 2 mA (4 mA)
Operation mode	CW and Pulsed
Maintenance	Hands-On (beam loss < 1 nA/m @ 40 MeV)

A. Nagler et al., LINAC 2006

21/9/2009 I. Mardor, SRF09, MOODAU04 2

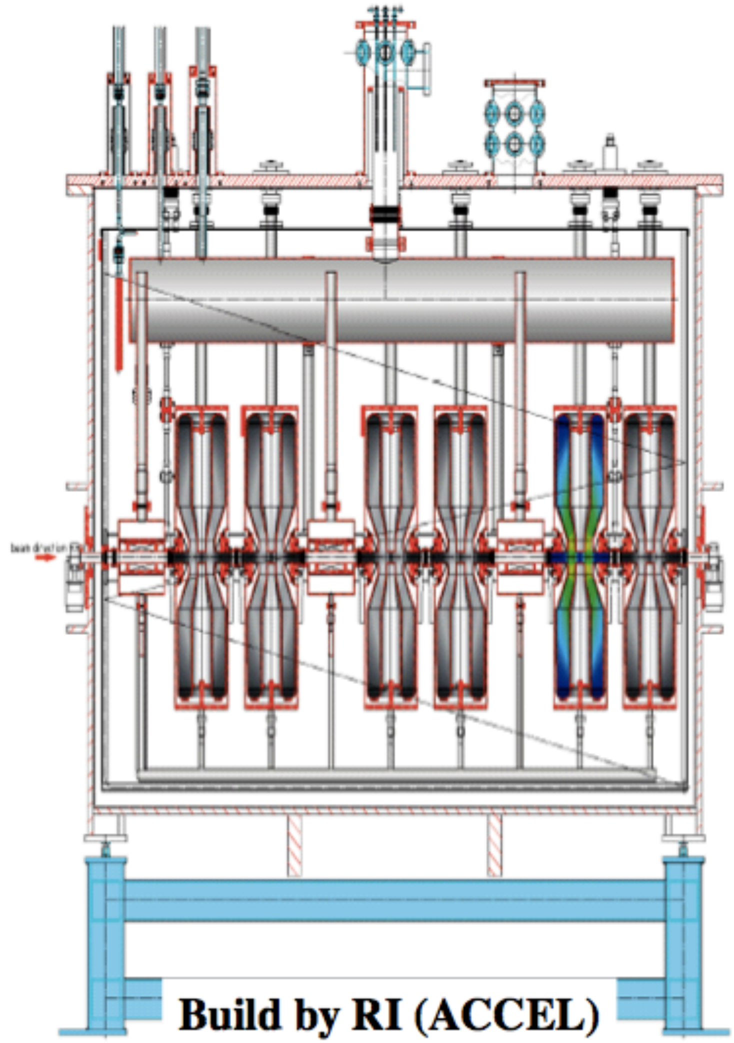
Specifications of PSM

Prototype Superconductive Module

SOREQ

- The cryomodule houses six SC HWR cavities and three SC solenoids
- Separate beam and insulation vacuum
- Operating temperature 4.2°K
- six 2 kW solid state amplifiers
- Designed to accelerate 2 mA protons or deuterons beams

HWR Parameters	
Frequency	176 MHz
Optimal β (protons)	0.09
$L_{acc}=\beta\lambda$	0.15 m
ΔV @ E_{peak}	840 kV @ 25 MV/m
Q_0@E_{peak}	$>4.7\times10^8$
Cryogenic load	< 70 W
Q_{ext} Loaded BW	$\sim1.3\times10^6$ ~130 Hz



Build by RI (ACCEL)

M. Pekeler, LINAC 2006

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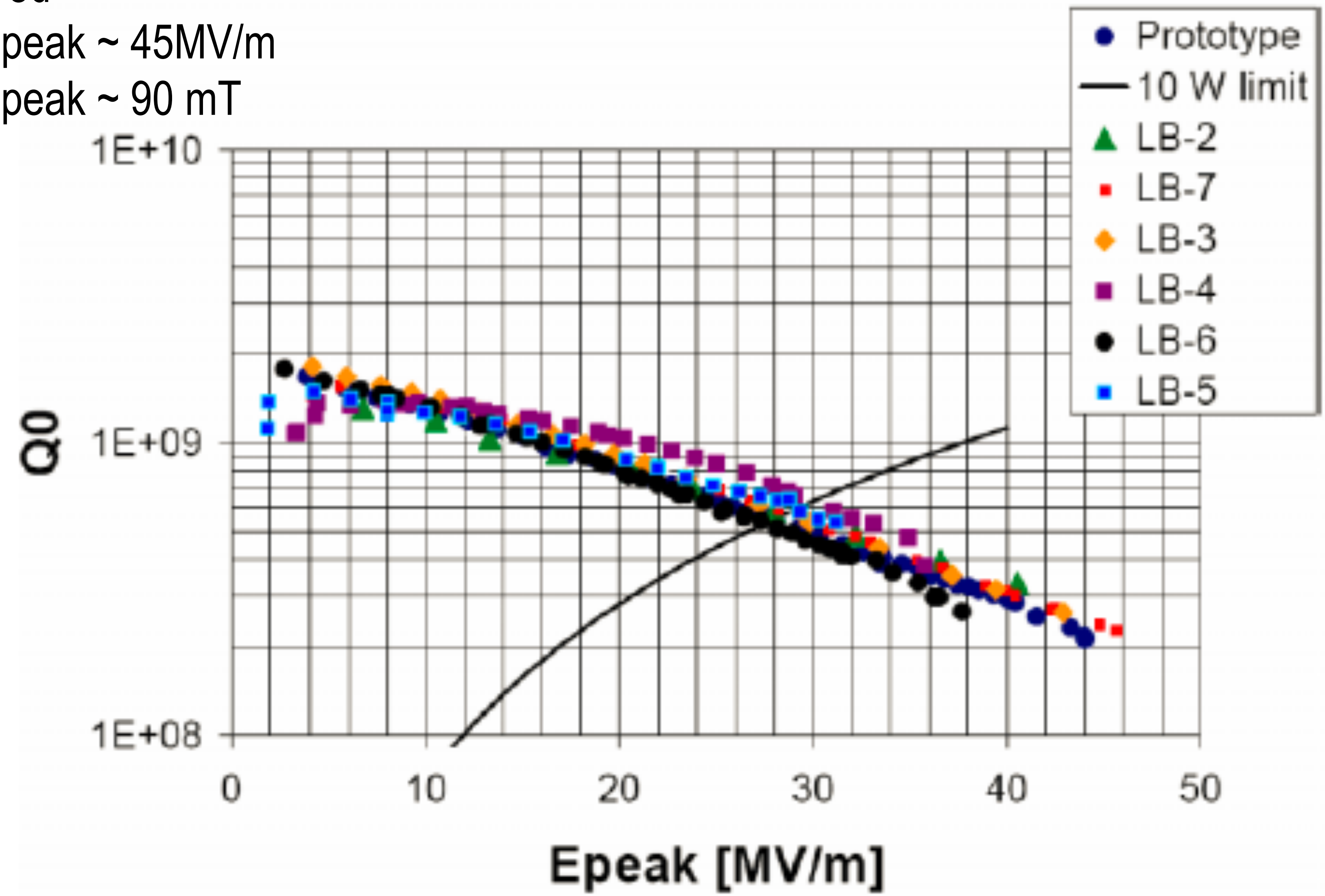
VTA Results

Achieved

Max Epeak ~ 45MV/m

Max Bpeak ~ 90 mT



Limits of Epeak in PSM

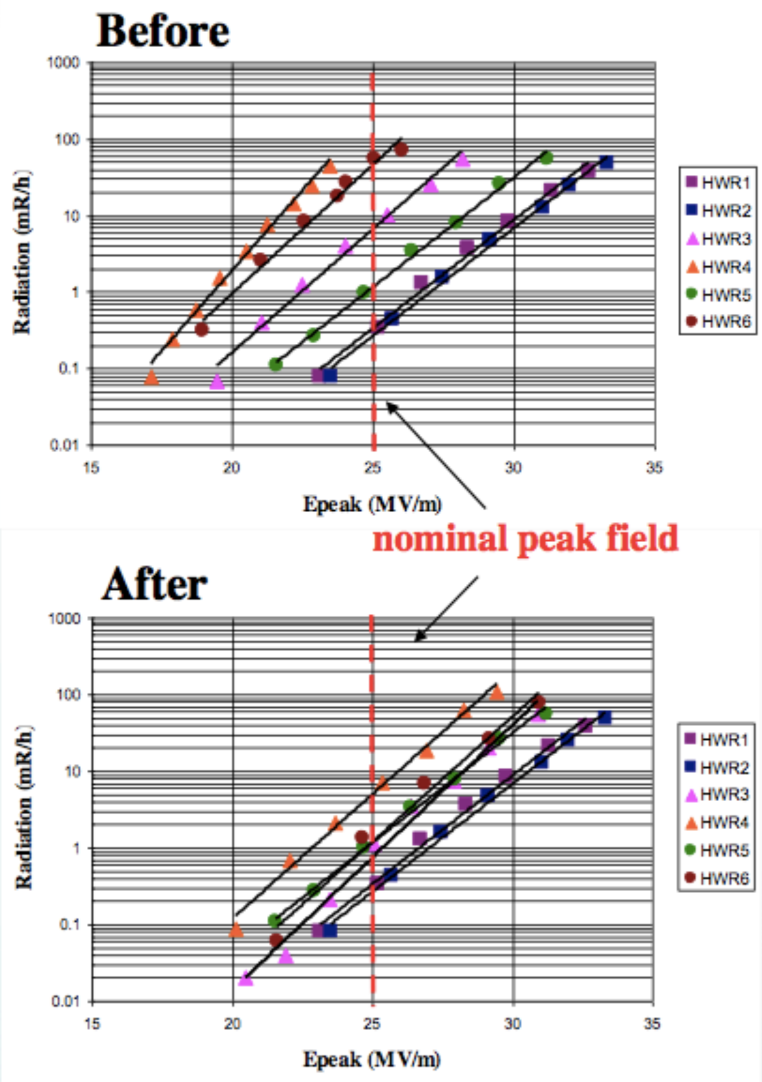
PSM commissioning

Helium processing :
99.9999% purity,
4 10^{-5} mbar
up to 43 MV/m 10% DC

Reduced field emission from the cavities and allowed stable operation at the nominal fields.

However, simultaneous operation of all cavities at the nominal field was not achieved for long period.

A. Perry, SRF2009



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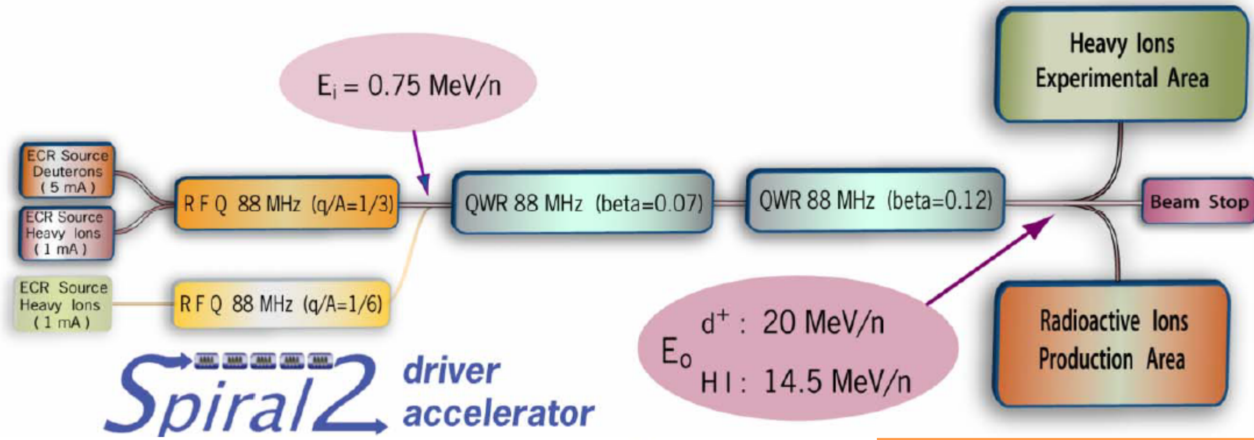
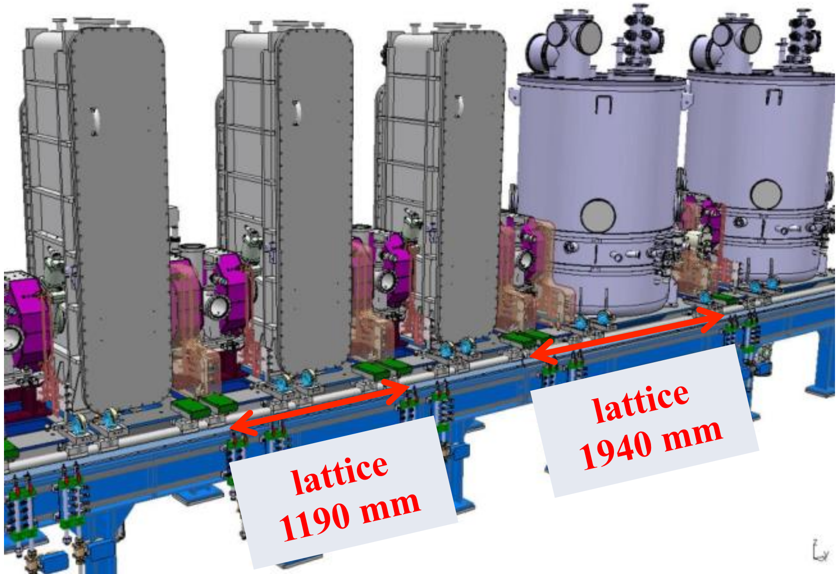
Layout of Spiral2

By Robin Ferdimand



Parameter	Value
Deuteron kinetic energy [MeV]	40
Deuteron Average current[mA]	5
Heavy Ion Average current [mA]	1



Cryomodule A	Cryomodule B	Power coupler
CEA Saclay	IPN Orsay	LPSC Grenoble

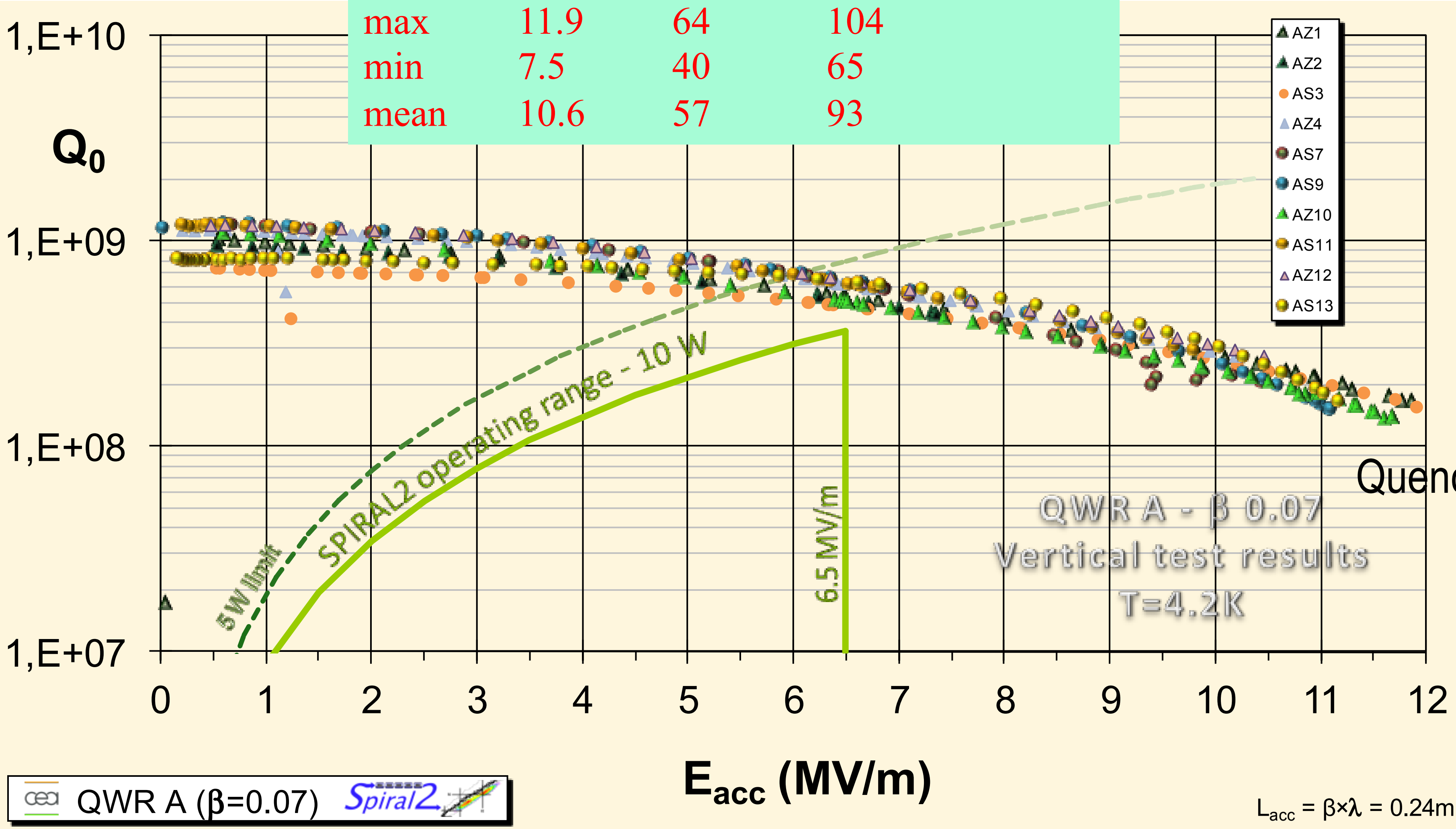
Cryomodule	A	B
# cavities	12	14
f [MHz]	88.05	88.05
β_{opt}	0.07	0.12
Epk/Ea	5.36	4.76
Bpk/Ea [mT/MV/m]	8.70	9.35
r/Q [Ω]	599	515
Vacc @ 6.5 MV/m & β_{opt}	1.55	2.66
Lacc [m]	0.24	0.41

β=0.07 cavity VT status

By Robin Ferdimand

Ep=35 MV/m
Bp=57 mT

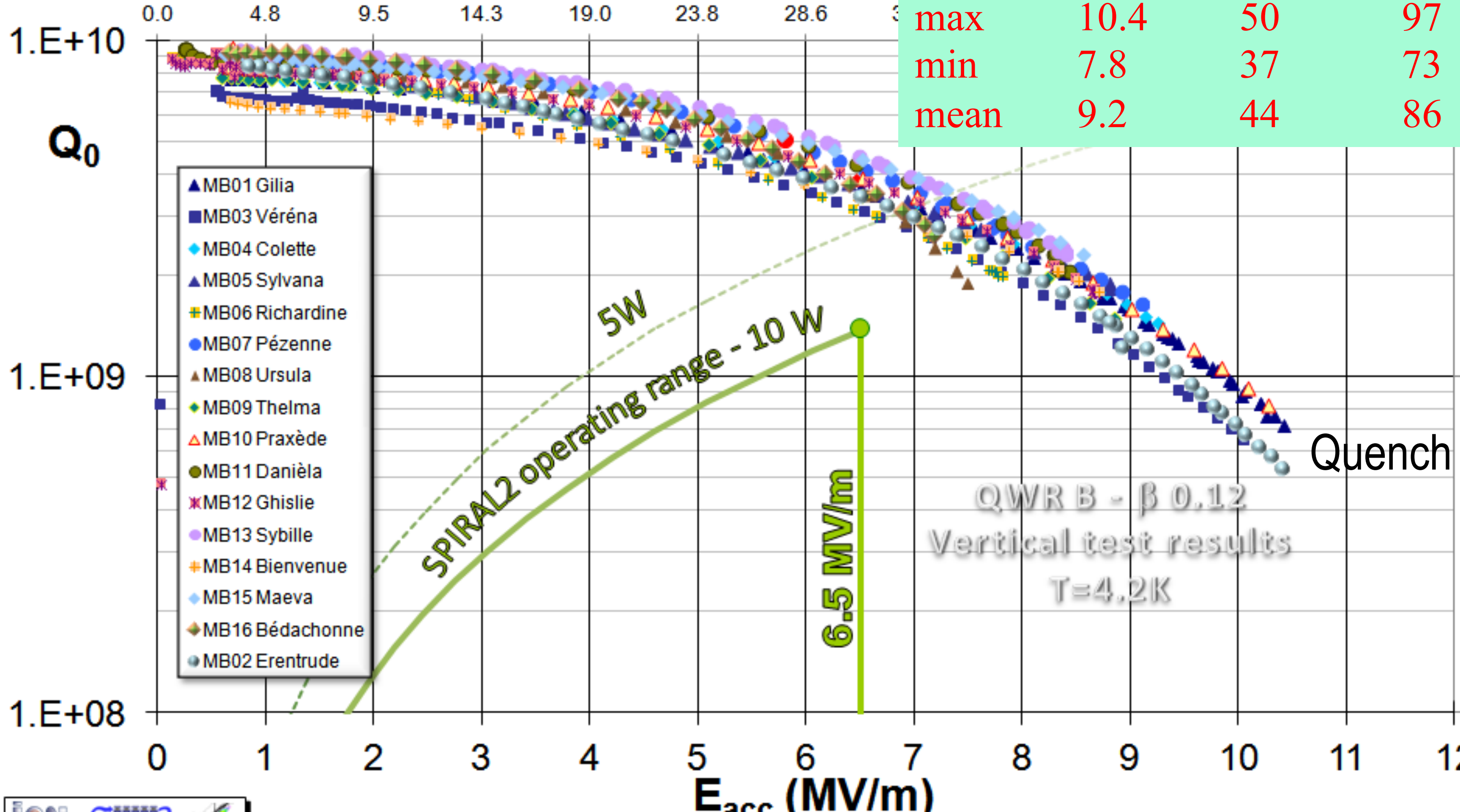
	Eacc MV/m	Epeak MV/m	Bpeak mT
max	11.9	64	104
min	7.5	40	65
mean	10.6	57	93



β=0.12 cavity VT status

Ep=31 MV/m
Bp=61 mT

	Eacc MV/m	Epeak MV/m	Bpeak mT
max	10.4	50	97
min	7.8	37	73
mean	9.2	44	86



$L_{acc} = \beta \times \lambda = 0.41$ m

Cryomodules status

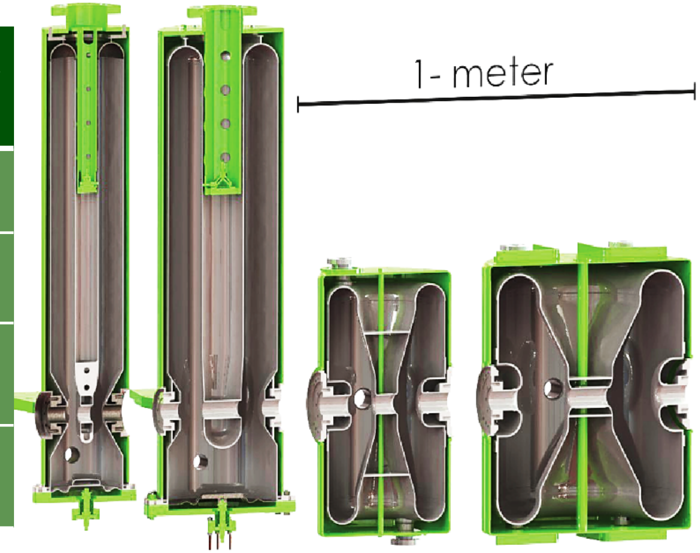
By Robin Ferdimand

	Unit	Specs	CMA4	CMA6	CMA7	CMA2	CMA3	CMA5	CMA9	CMA8
Max. acc. Gradient	MV/m	>6.5	8.85	8.34	9	8.6	7.95	9.1	8.44	9
Rx activity @6.5MV/m	µSv/h		560	91	14.3	730	494	1.5	677	32
Total losses @4K, 6.5MV/m	W	<20.5	20.8	11.4	11.8	15.56	17.9	11.3	12.6	10.38
Static losses @4K	W	<8.5W	6.5	3.98	4.1	3.11	4.34	3.6	4.47	3.12
Pressure sensitivity	Hz/mbar	<5	-1.58	-1.32	-1.45	-1.31	-1.08	-1.22	-1.24	-1.66
Cavity alignment	mm	◎ 1.3	0.52	0.4	0.48	1.46	0.4			
	Unit	**Specs**	**CMB1**		**CMB2**		**CMB3**		**CMB4**	
Max. acc. Gradient	MV/m	> 6.5	>8.0	>8.0	>8.0	>8.0	>8.0	>8.0	>8.0	>8.0
Rx activity @6.5MV/m	µSv/h		22000	0	160	0	0	0	70	0
Total losses @4K, 6.5MV/m	W	< 36.0	29		29		27		31.5	
Static losses @4k	W	<12.5	17		19		19		19	
Pressure sensitivity	Hz/mbar	< 8.0	-5.3	-4.95	-5.4	-5.8	-5.2	-4.5	-4.9	-5.2
Beam vacuum	mbar	< 5.0e-7	5E-08		3E-08		4E-08		6E-08	
Cavity alignment	mm	◎ 1.2	0.16	0.34	0.62	0.42	0.24	0.38	0.14	0.36

In order to avoid damages, the max allowed test cavity field value for the A type cryomodule is 9MV/m, and 8MV/m for the B type cryomodule (respectively Epeak=48MV/m and 38MV/m and Bpeak=78mT and 75mT).

Layout of FRIB

Cavity Type	Frequency & Cavity type	R/Q Ω	Ep/Eacc	Hp/Eacc mT/(MV/m)	Specification@2K Eacc(MV/m)/Qo
β=0.041	80.5 MHz, QWR	401.6	6.1	10.8	5.1 / 1.4E+9
β=0.085	80.5 MHz, QWR	451.6	5.9	12.5	5.6 / 2.0E+9
β=0.29	322MHz, HWR	224.4	4.3	7.7	7.7 / 6.7E+9
β=0.53	322MHz, HWR	229.5	3.6	8.6	7.4 / 9.2E+9

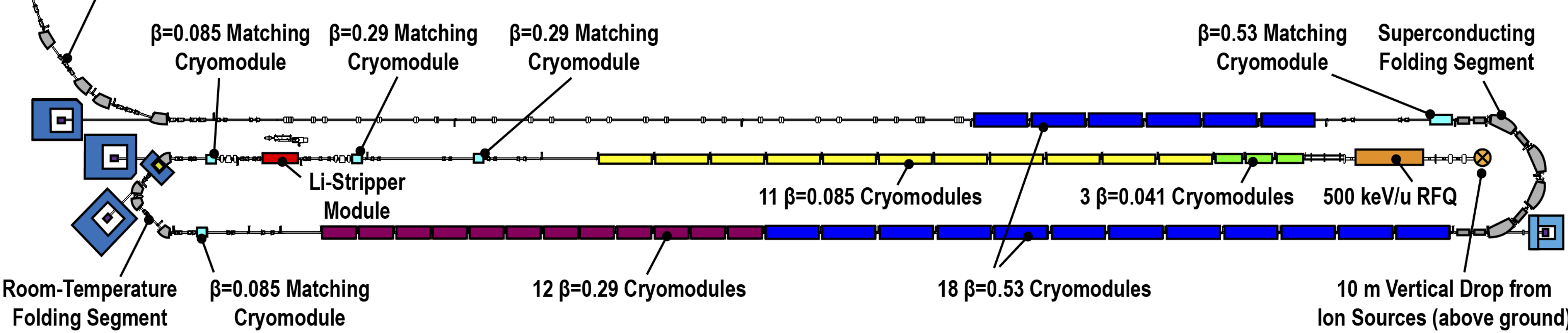


β_0 = 0.041 β_0 = 0.085 β_0 = 0.29 β_0 = 0.53

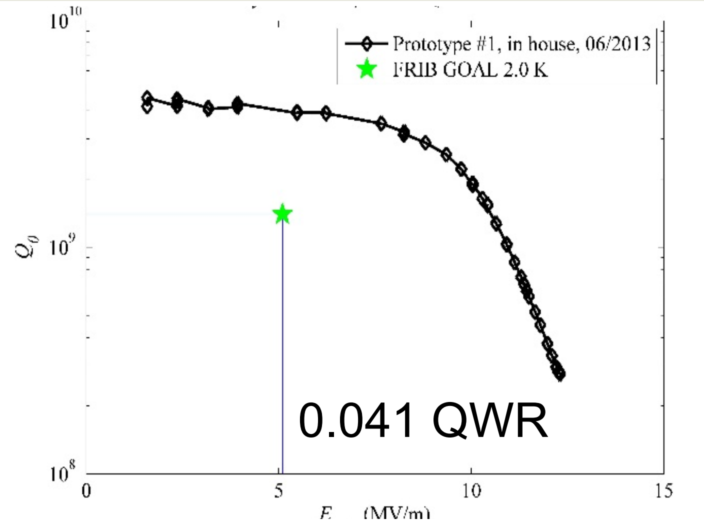
Quarter-Wave Resonators 80.5 MHz

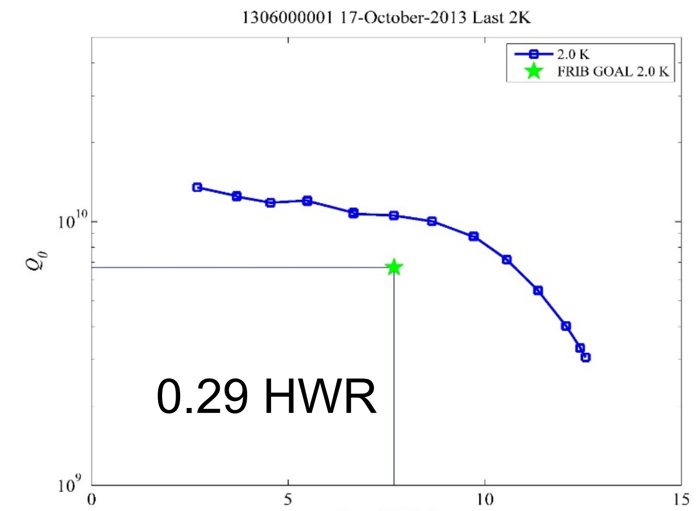
Half-Wave Resonators 322 MHz

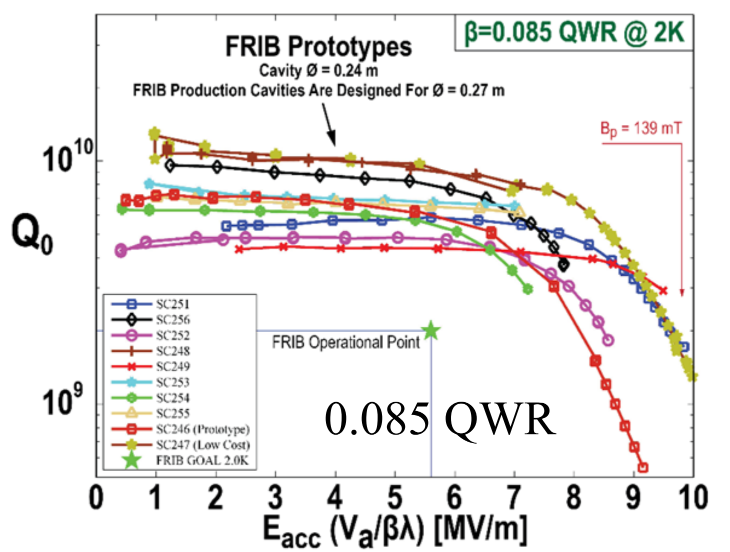
Heavy ion < 1emA

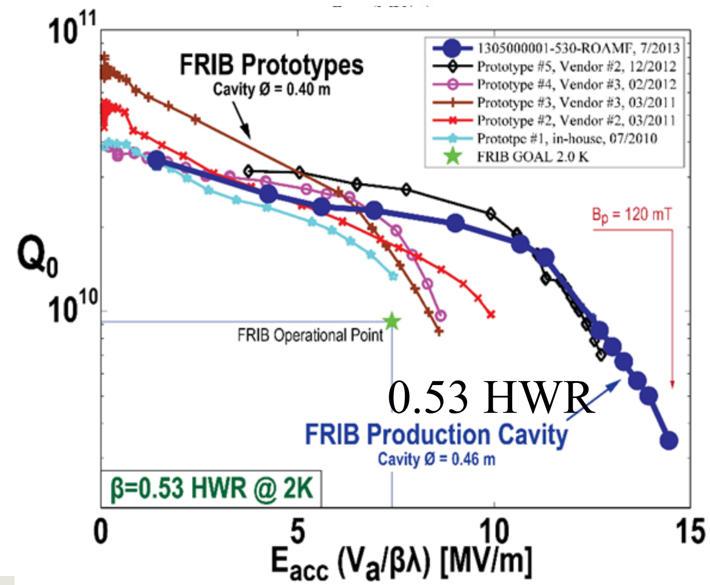


Cavity Certificate Results and Limitation







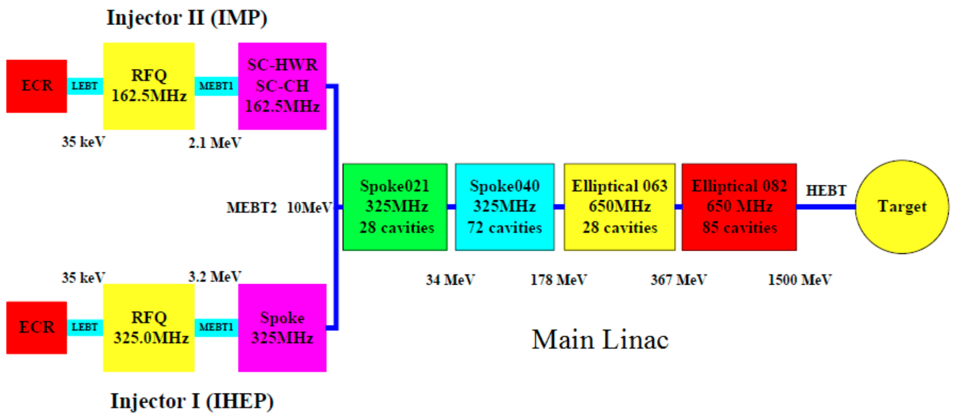


- **All 4 types have been successfully qualified with an enough margin for FRIB specification.**
- **High Q slope and Field emission also limits the gradient in some cases.**
- **He vessel dressing has no impact on cavity performance.**
- **120^{O}C baking helps for high Q and conditioning low level multipacting**

QWR0.041
Ep=31 MV/m, Bp=55 mT
QWR0.085
Ep=33 MV/m, Bp=70 mT
HWR0.29
Ep=33 MV/m, Bp=60 mT
HWR0.53
Ep=27 MV/m, Bp=64 mT

By Kanji Saito

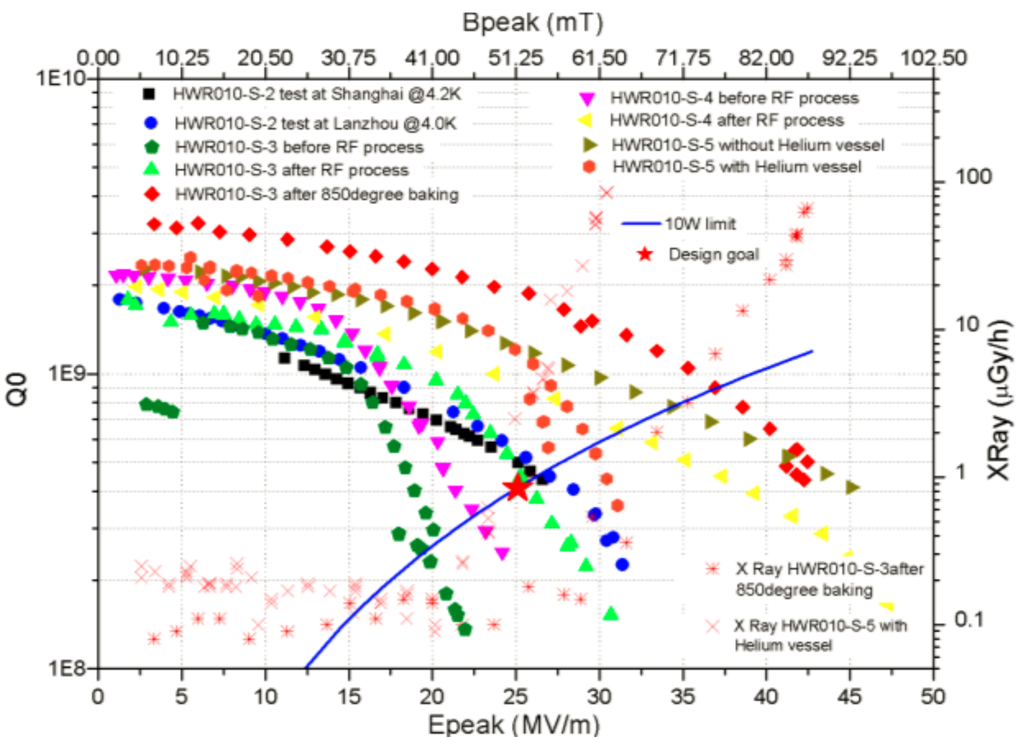
SRF Cavities for China ADS Project

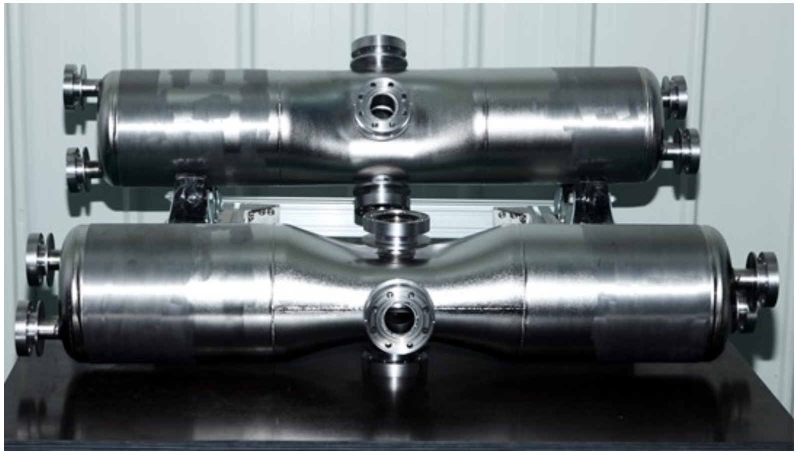


Parameters	Value
Ions	P
Energy	0.25~1.5 GeV
Current	10 mA

	Unit	Spoke012	HWR010	HWR015	Spoke021	Spoke040	Ellip063	Ellip082
Freq.	MHz	325	162.5	162.5	325	325	650	650
βg	-	0.12	0.09	0.14	0.21	0.4	0.63	0.82
Aperture	mm	35	40	40	50	50	100	100
Va max	MV	0.82	0.78	1.82	1.64	2.86	10.26	15.63
Epeak	MV/m	32.5	25	32	24/31	25/32	29/38	28/36
Bpeak	mT	46	50	40	50/65	50/65	50/65	50/65
Temp.	K	4.5	4.5	4.5	4.5	2	2	2
Ploss	W	10	10	15.5	16.8	6.5	21	39

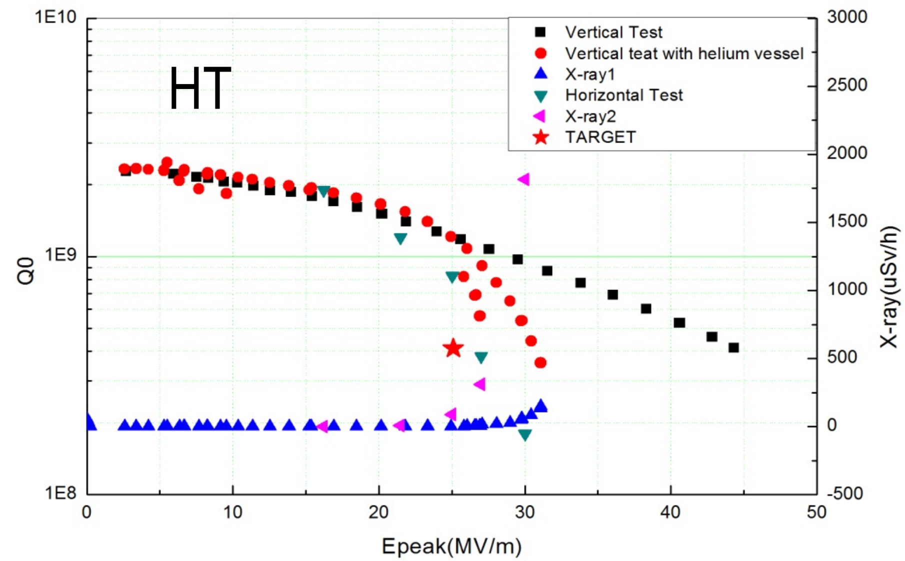
VT and HT Results of HWR



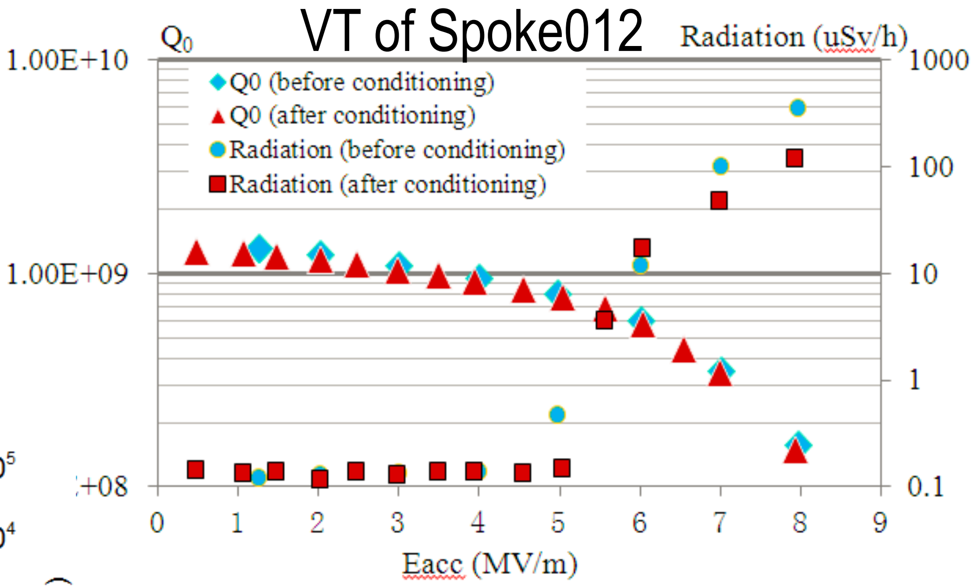


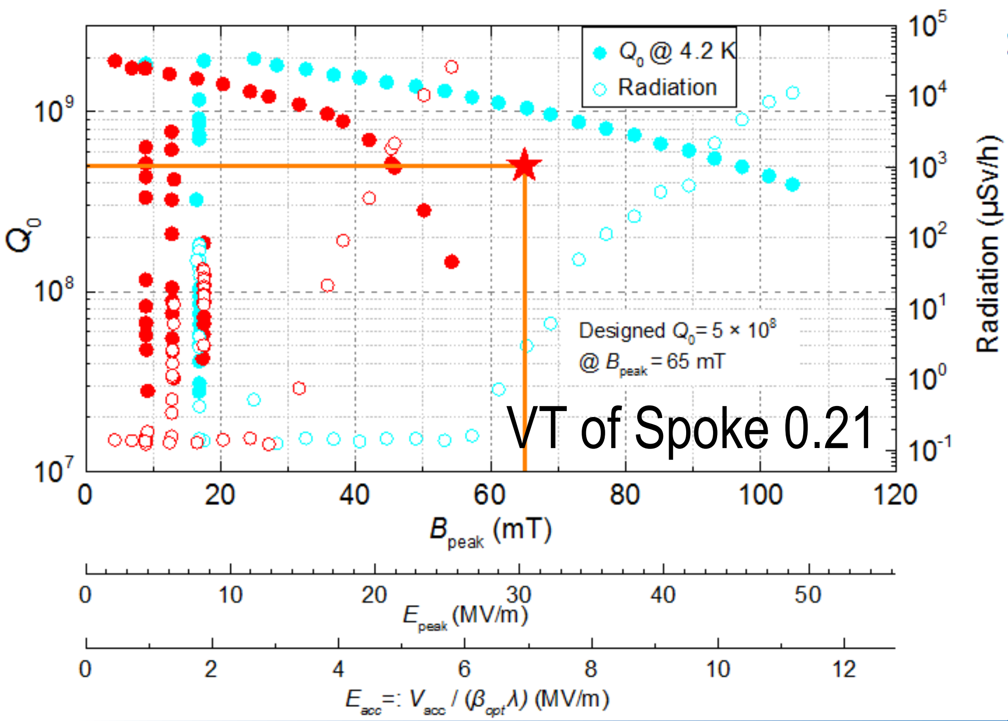
HWR 0.10

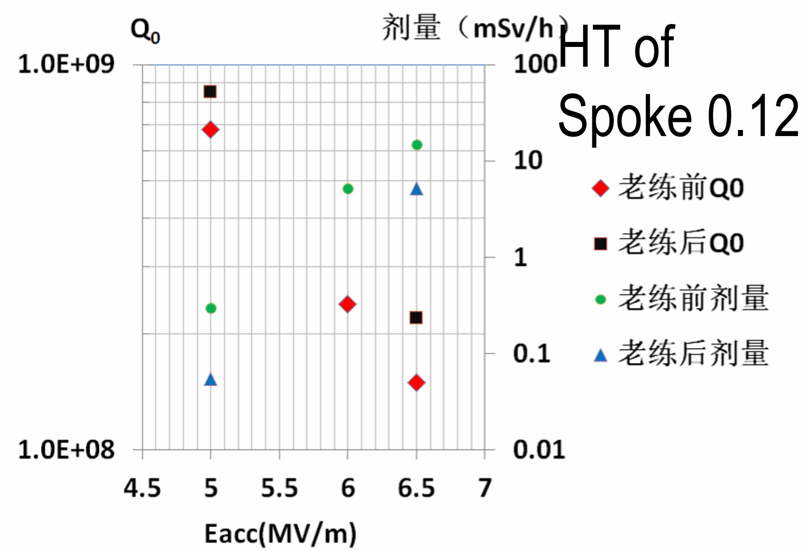
1. Q-slop is observed for all cavities.
2. MP happens at very low field during every testing but #02 at IMP.
3. Field Emission of HWR #03, #04 is very heavy
4. FE is the mainly trouble to achieve higher.



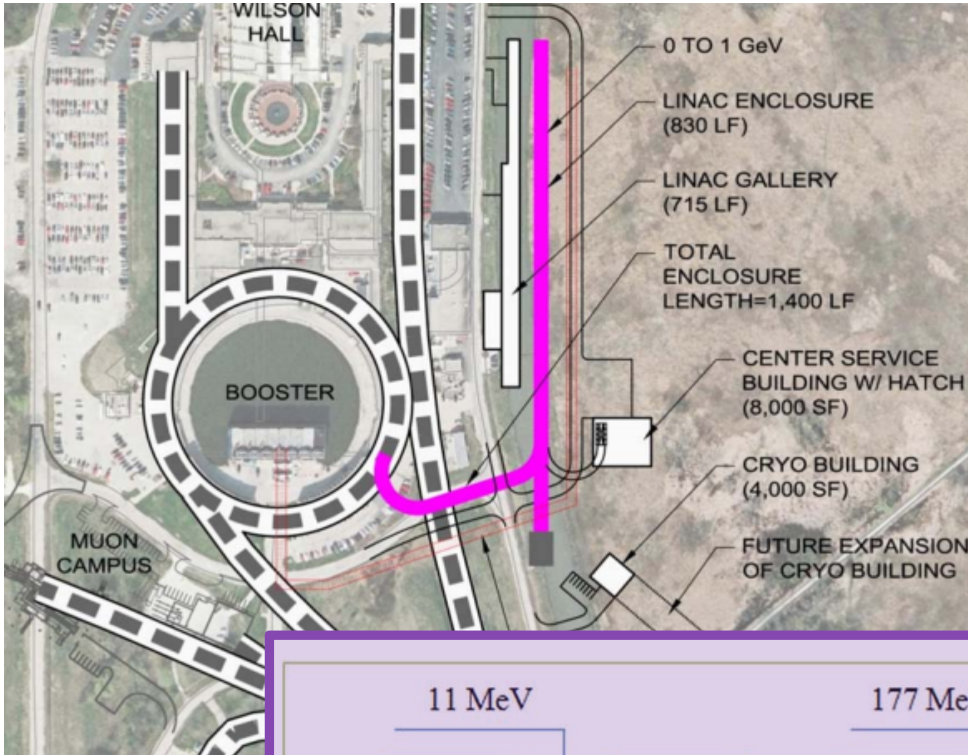
Test Results of Spoke012 and 021







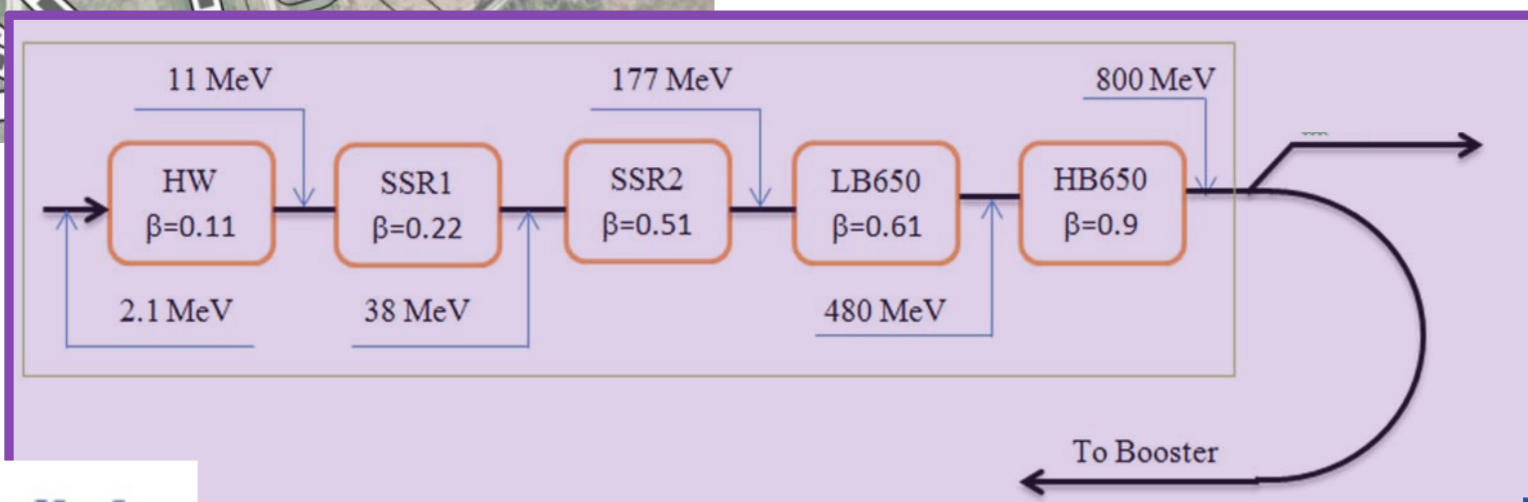
Layout of Proton Improvement Plan II



XMAC, February 2014; Slava Yakovlev

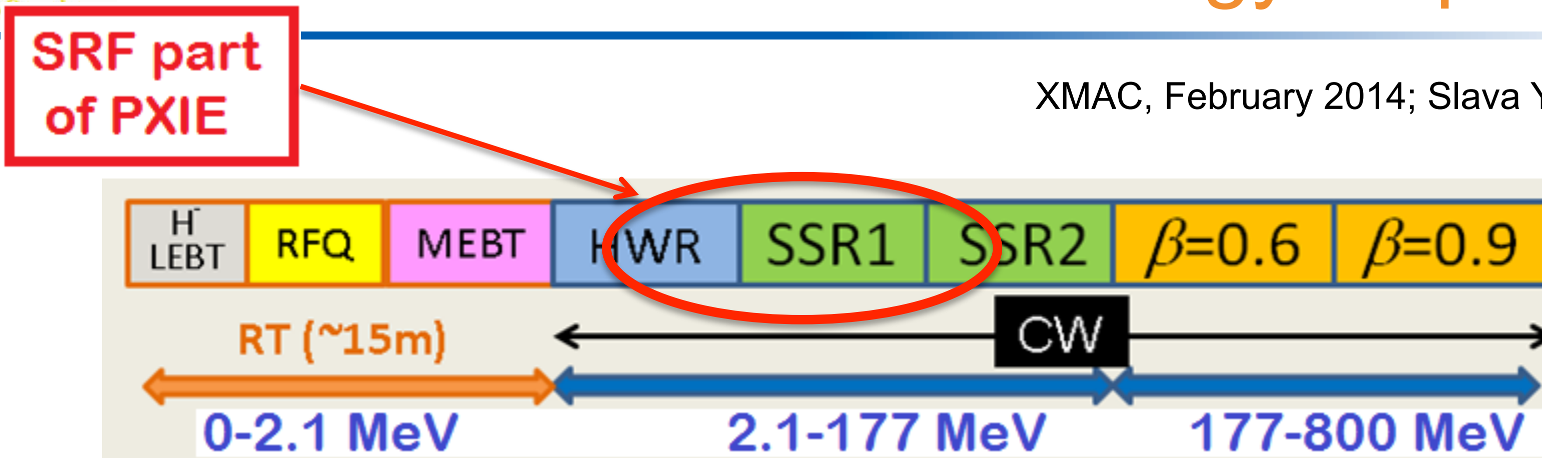
Linac Beam Energy	800	MeV
Linac Beam Current	2	mA
Linac Beam Pulse Length	0.6	msec
Linac Pulse Repetition Rate	15	Hz
Linac Upgrade Potential	CW	

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



PIP II SRF Linac Technology Map

XMAC, February 2014; Slava Yakovlev

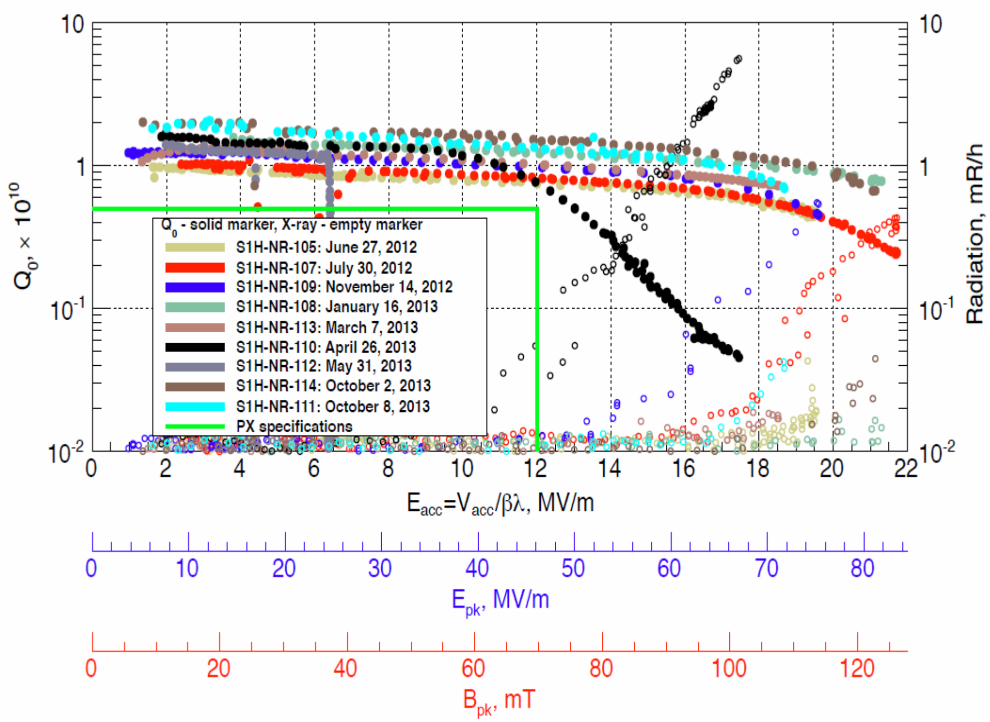


Name	Freq (MHz)	Cavity	Eacc (MV/m)	Epeak (MV/m)	Bpeak (mT)	ΔE (MeV)	Energy (MeV)	CM	Cavity / CM	Q0@2K (10^{10})	Static loss/ CM @2 K, W	Total loss /CM @2 K CW, W
HWR	162.5	HWR	8.2	38	41	1.7	2.1-11	1	8	0.5	14	24
SSR1	325	Single-spoke	10	38	58	2.05	11-38	2	8	0.5	16	27
SSR2	325	Single-spoke	11.2	40	70	5.32	38-177	7	5	1.2	8.8	52
LB650	650	Elliptic 5cell	16.5	37.5	70	11.6	177-480	5	6*	1.5	8.1	153
HB650	650	Elliptic 5cell	17.5	35.2	64	17.7	480-800	4	6	2	6.2	153

- $E_{peak} \leq$ 40 MV/m, for CW (Field emission);
- $B_{peak} \leq$ 75 mT, for CW (medium field Q-slope)

- In CW regime the total loss is 410 W;
- 5% duty factor for cryo, or 20.5 W.

325 MHz beta=0.22 SSR1 cavity



XMAC, February 2014; Slava Yakovlev

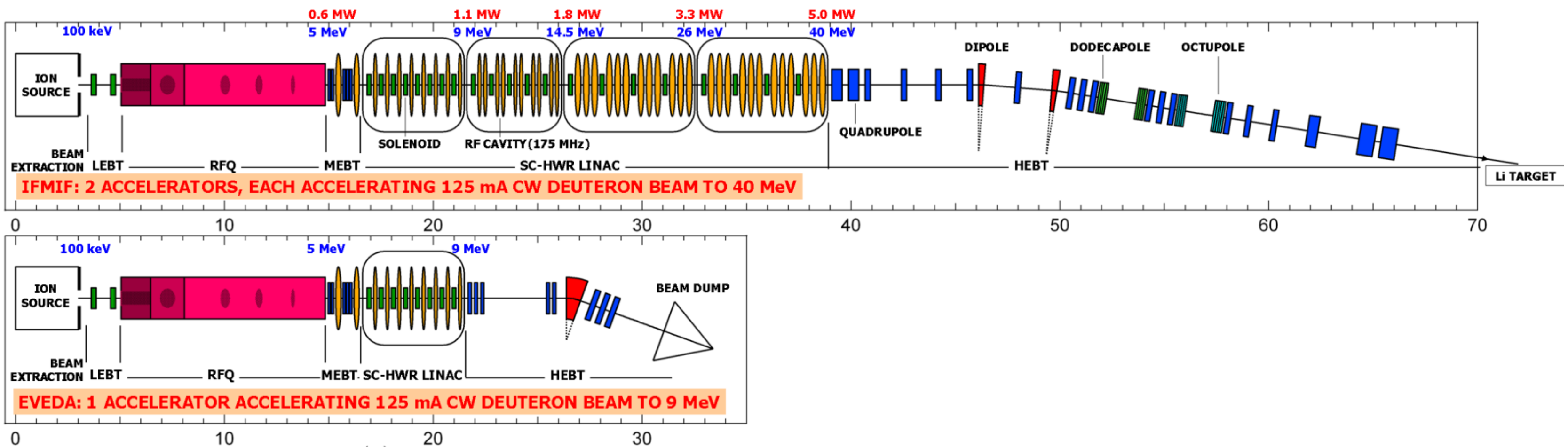
- 120-150 micron BCP and HPR at ANL/FNAL processing facility then 120 C bake
- Low FE depends on optimized nozzle design for effective HPR of surface

- Two previous SSR1 spoke resonators performed very well in bare cavity tests;
- Above are the tests of 9 cavities from U.S. Vendor (Roark) production of 10 cavities;
- Performance at 2 K is above requirements for Project X in both Q_0 and gradient.

SSR1 Prototypes Exceed PX Performance Specs.

IFMIF/EVEDA: scope of the Project

- International Fusion Material Irradiation Facility (IFMIF): 2 accelerators in parallel
- Each accelerator: 125 mA deuteron beam, 40 MeV, CW
- EVEDA (Engineering Validation and Engineering Design Activities): first phase to validate the key technologies

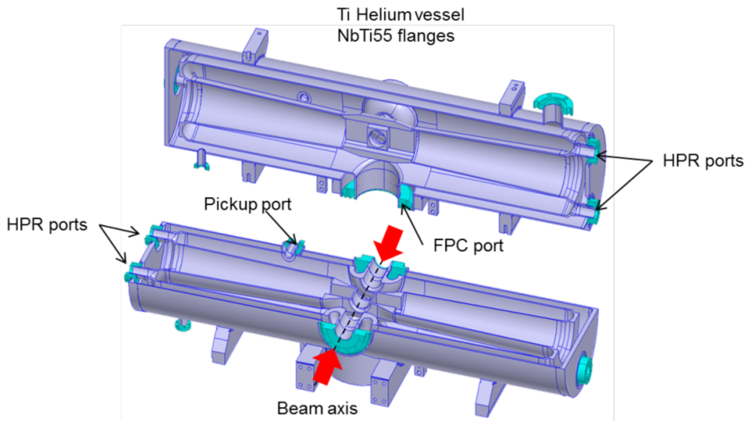


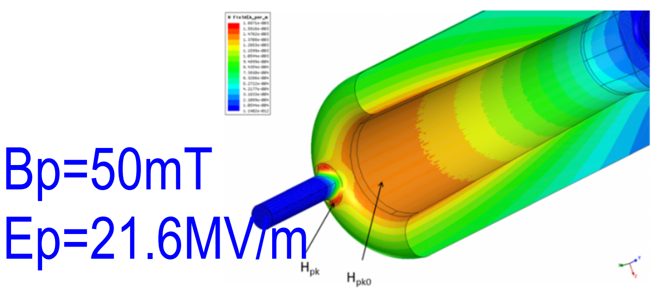
- Linear IFMIF Prototype Accelerator (LIPAc) to be tested at Rokkasho – Japan
- International collaboration between Europe and Japan

By Alban Mosnier

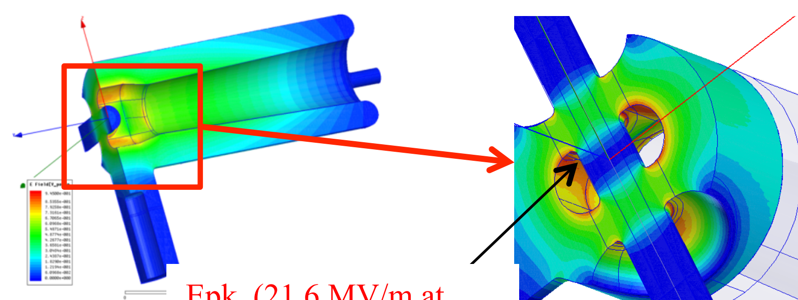
IFMIF HWR Design

By Alban Mosnier





Hpk located on HPR port



Epk (21.6 MV/m at nominal gradient)

Requirements

PARAMETER	VALUE
Beam port diameter [mm]	40
Nominal accelerating gradient [MV/m]	4.5
Operation temperature [K]	4.45
Quality factor at nominal accelerating gradient	>5E8
Power dissipation at nominal accelerating gradient (W)	< 7
Nominal beta	0.094
Tuning range [kHz]	50
External Q (Qext)	6.5e4
Loaded cavity bandwidth [kHz]	2.7

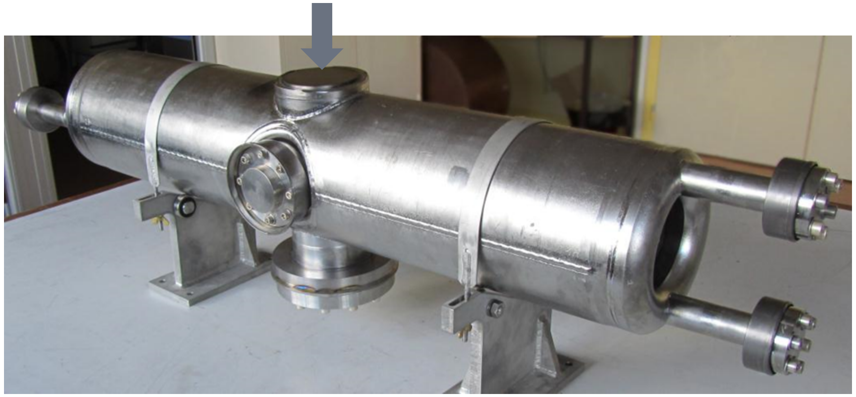
Extra design constraints:

- Power coupler port diameter of 98 mm
- Cold frequency tuning performed by means of cavity deformation
- Compliance with Japanese pressure vessels regulation

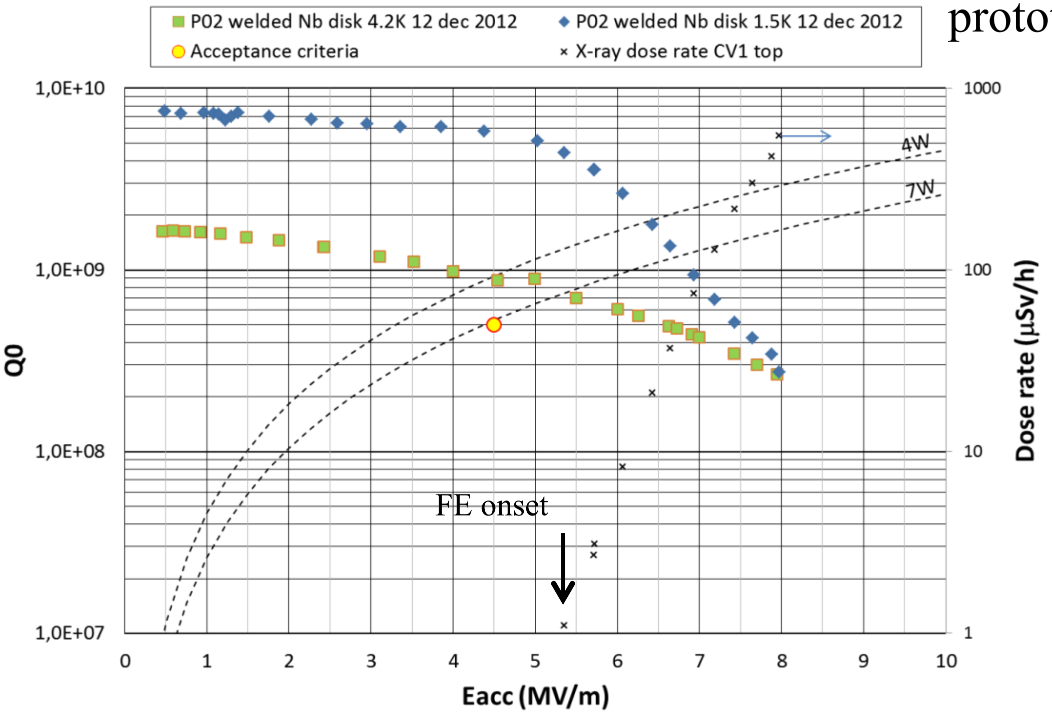
RF Characteristics

	unit	value
Frequency	MHz	175
Epk/Eacc		4.8
Bpk/Eacc	mT/(MV/m)	11
G	Ω	26.3
R/Q at β_{opt}	Ω	151
R/Q at $\beta = 0.094$	Ω	140
Qo at low field T=4.45 K		1.3e9

Prototype: Vertical Test Results



- ❑ Prototypes based on the original design with central plunger tuner
- ❑ Modified in 2012-2013 to overcome the limitations of the plunger flange/gasket poor RF and thermal behavior
- ❑ NbTi plunger flange removed and port closed with Nb disk
- ❑ More details about the qualification of the prototypes in N. Bazin's paper at SRF 2013

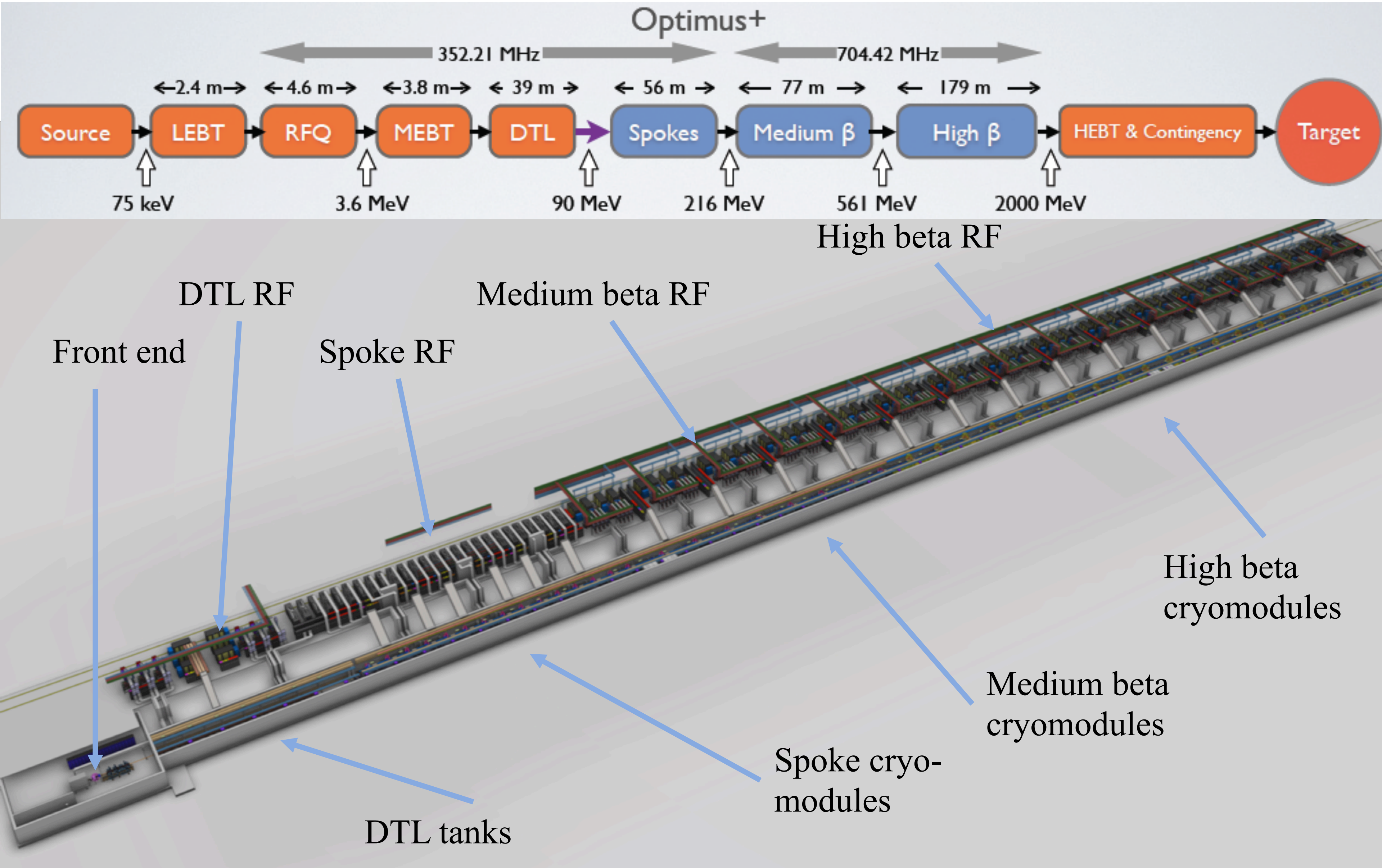


- ❑ FE onset at 5.4 MV/m
- ❑ HWR prototype qualified
- ❑ RF design validated

By Alban Mosnier

ESS Linac Layout

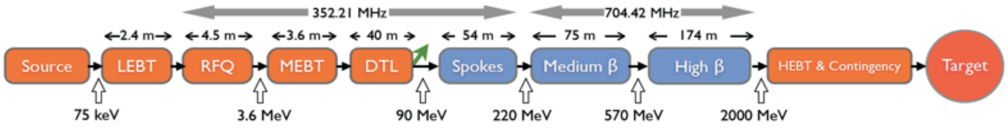
By Steve Malloy

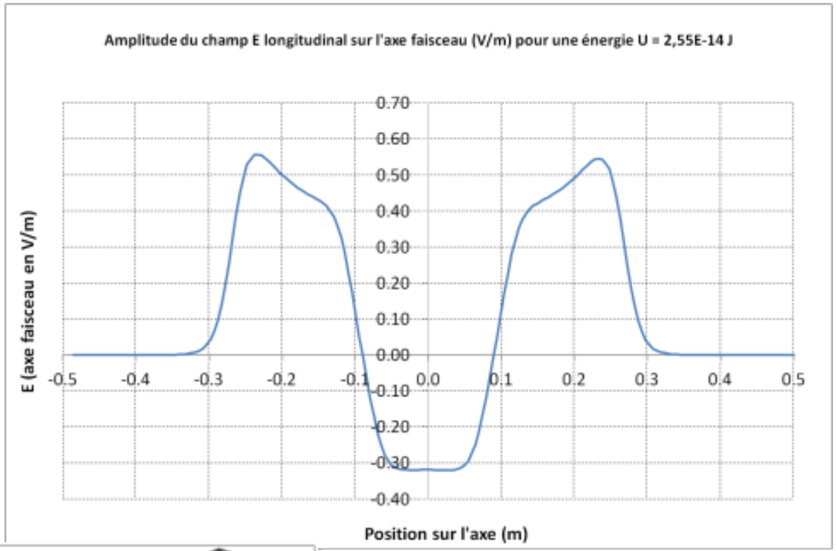


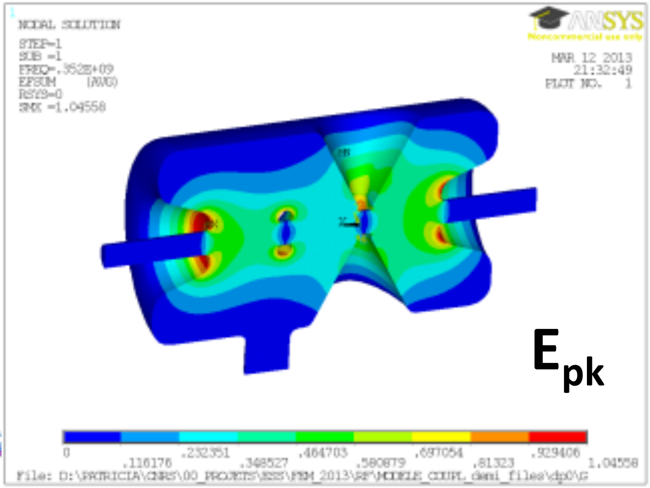
Spoke Cavity RF design

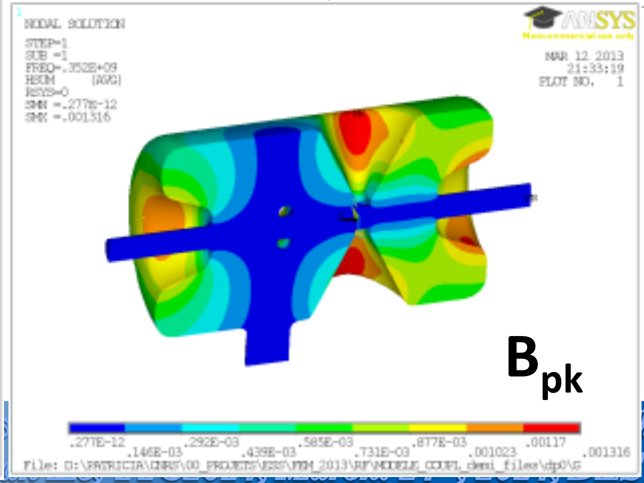
By Steve Malloy

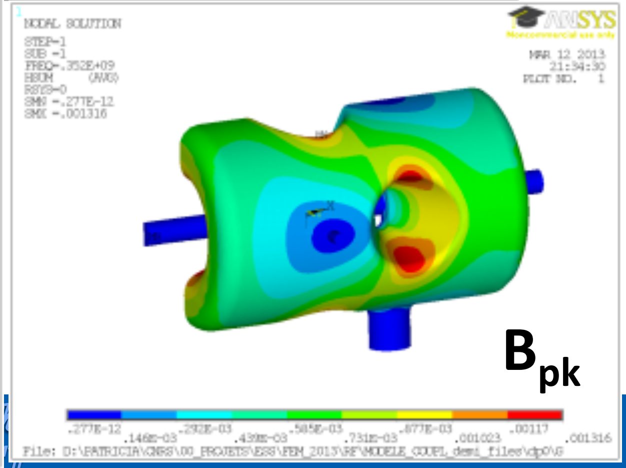
DOUBLE-SPOKE CAVITY	
Frequency [MHz] **Req. 1**	352.21
Beta_optimum **Req. 5**	0.50
Operating gradient [MV/m] **Req. 6**	9
Temperature (K)	2
Bpk [mT]	61
Epk [MV/m]	38
G [Ohm]	133
r/Q [Ohm]	427
Lacc (=beta optimal x nb of gaps x λ /2) [m]	0.639
Bpk/Eacc [mT/MV/m]	6.8
Epk/Eacc	4.3
P max [kW]	335





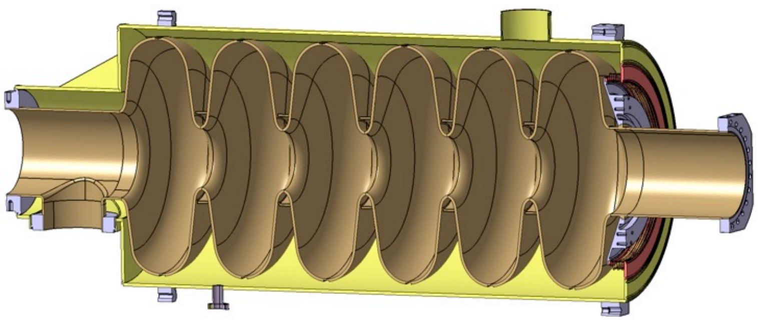




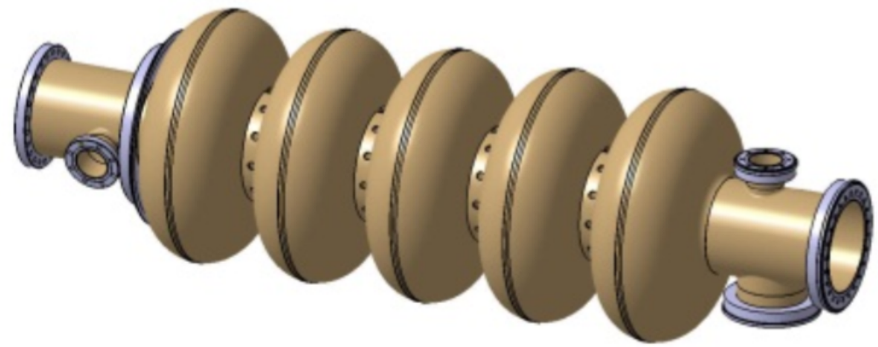


Elliptical cavity design

By Steve Malloy



β=0.65



β=0.86

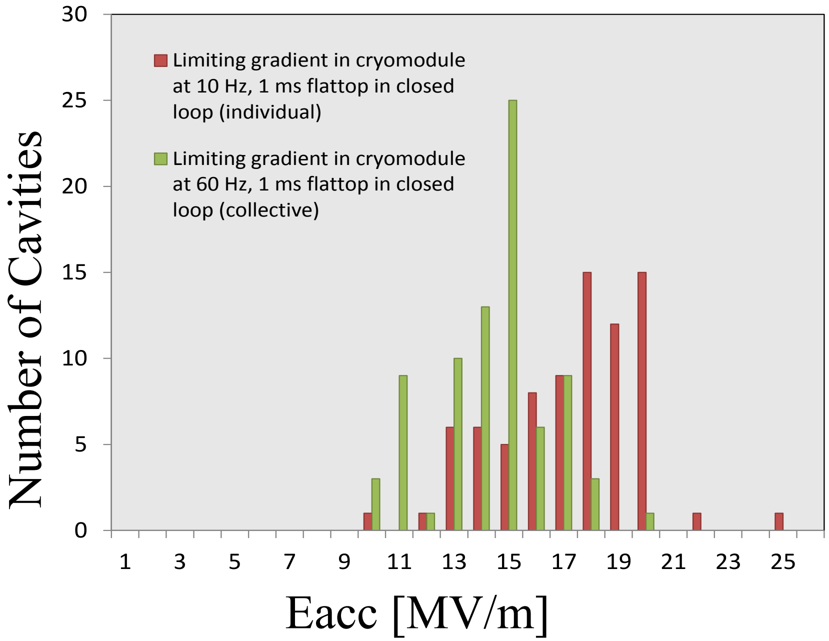
	Medium	High
Geometrical β	0.67	0.86
Frequency (MHz)	704.2	704.2
Number of cells	6	5
Temperature (K)	2	2
Max surface E field (MV/m)	44	44
Peak B field (mT)	80	85
Nominal gradient (Mv/m)	16.7	19.9
Q0 at nominal gradient	>5e9	>5e9
Qext	7.50E+05	7.60E+05

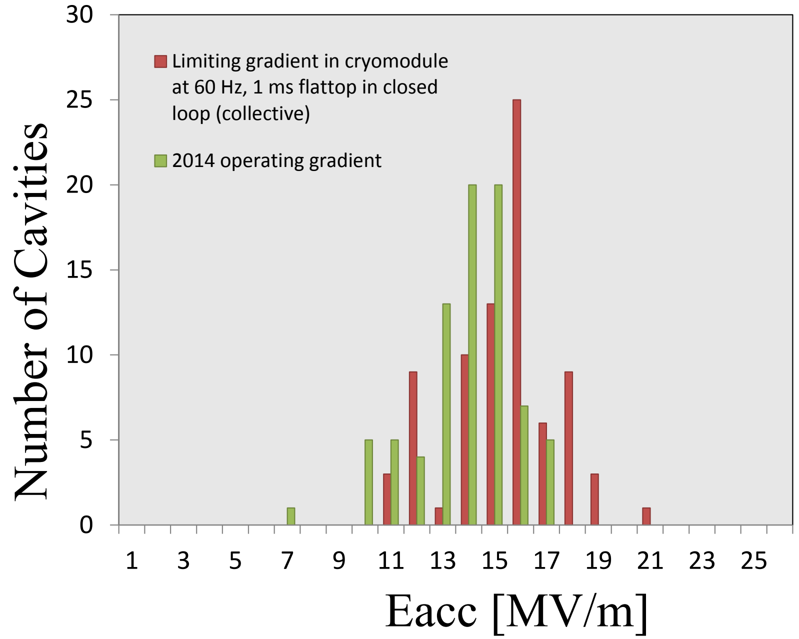
Limit by the main coupler power <1.1 MW

Limit of Gradient at SNS

- Field emission induced heating (major limiting factor for both types of cavities)
- At higher duty factor (>30 Hz) collective effect affects achievable gradients. Operation at 60 Hz, a few cavities operating much lower gradient than limiting gradient.
- MP of HOM couplers. MP induced radiation → radiation onset is very low especially in high beta cavities. Field emission onset is higher than radiation onset gradient.

By Sang-Ho Kim





Effect of High Oder Modes

- SNS removed many feedthroughs from HOM couplers.
- SNS re-evaluated the HOM issues and concluded that the SNS does not need HOM damping in 2007.
- Still achievable gradients are limited by HOM couplers in several cavities. Very careful conditioning is required after thermal cycle.

By Sang-Ho Kim

XMAC, February 2014; Slava Yakovlev

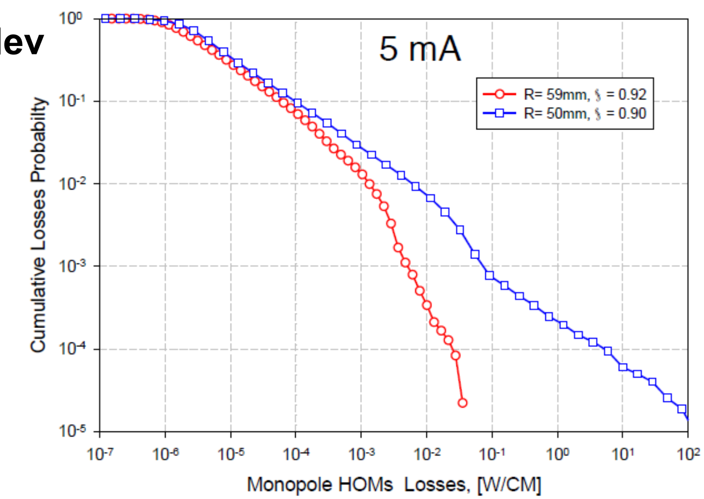
- **CW regime:**

Probability of HOM excitation is very small. BBU is not an issue.
Incoherent losses: 2.8 W/CM compared to 200 W/CM of RF load (beam current is 2 mA).

- **Pulsed regime:**

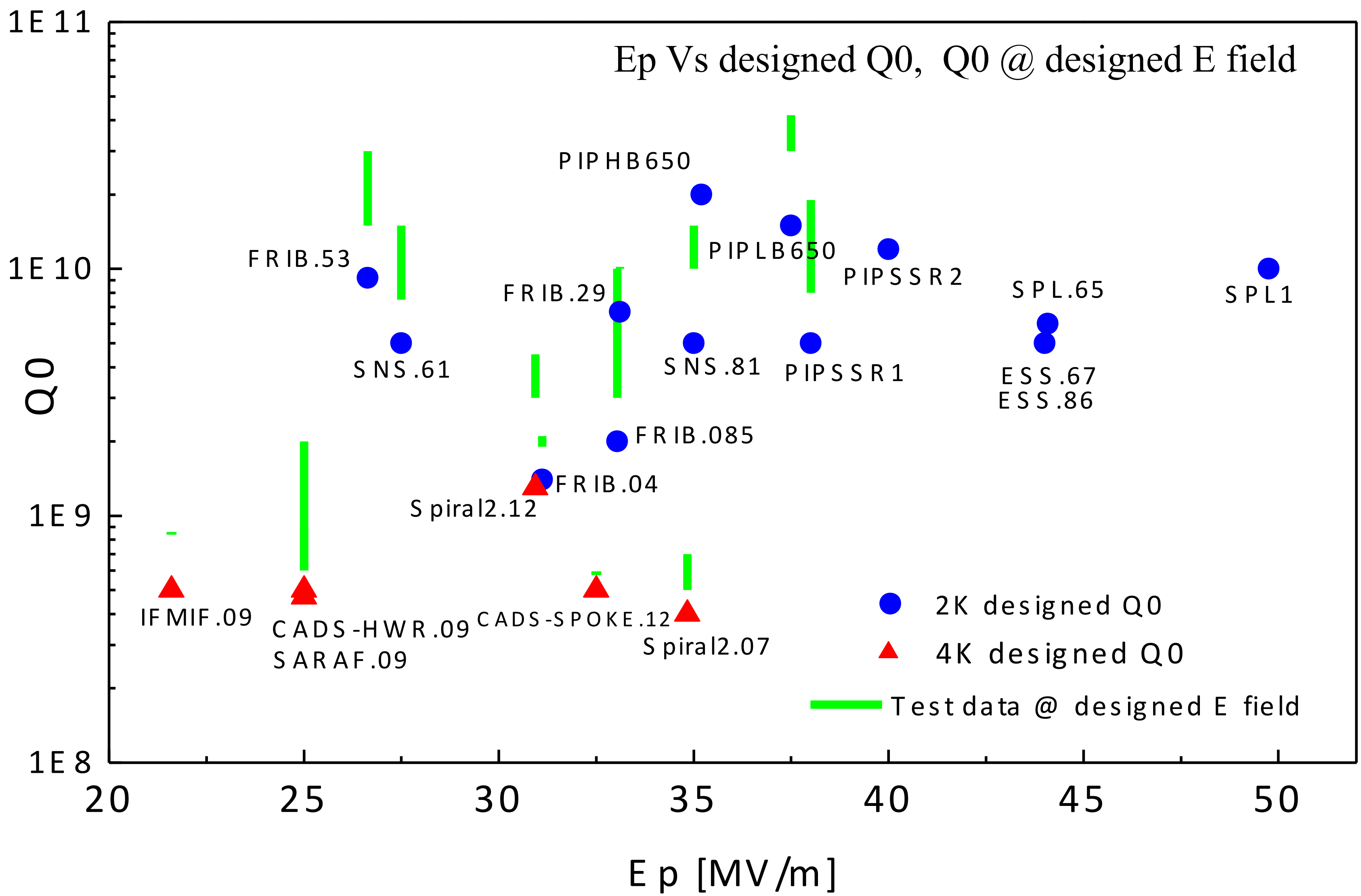
Duty factor is 0.9%, incoherent losses are 25 mW/CM.

HOMs should not be an issue.

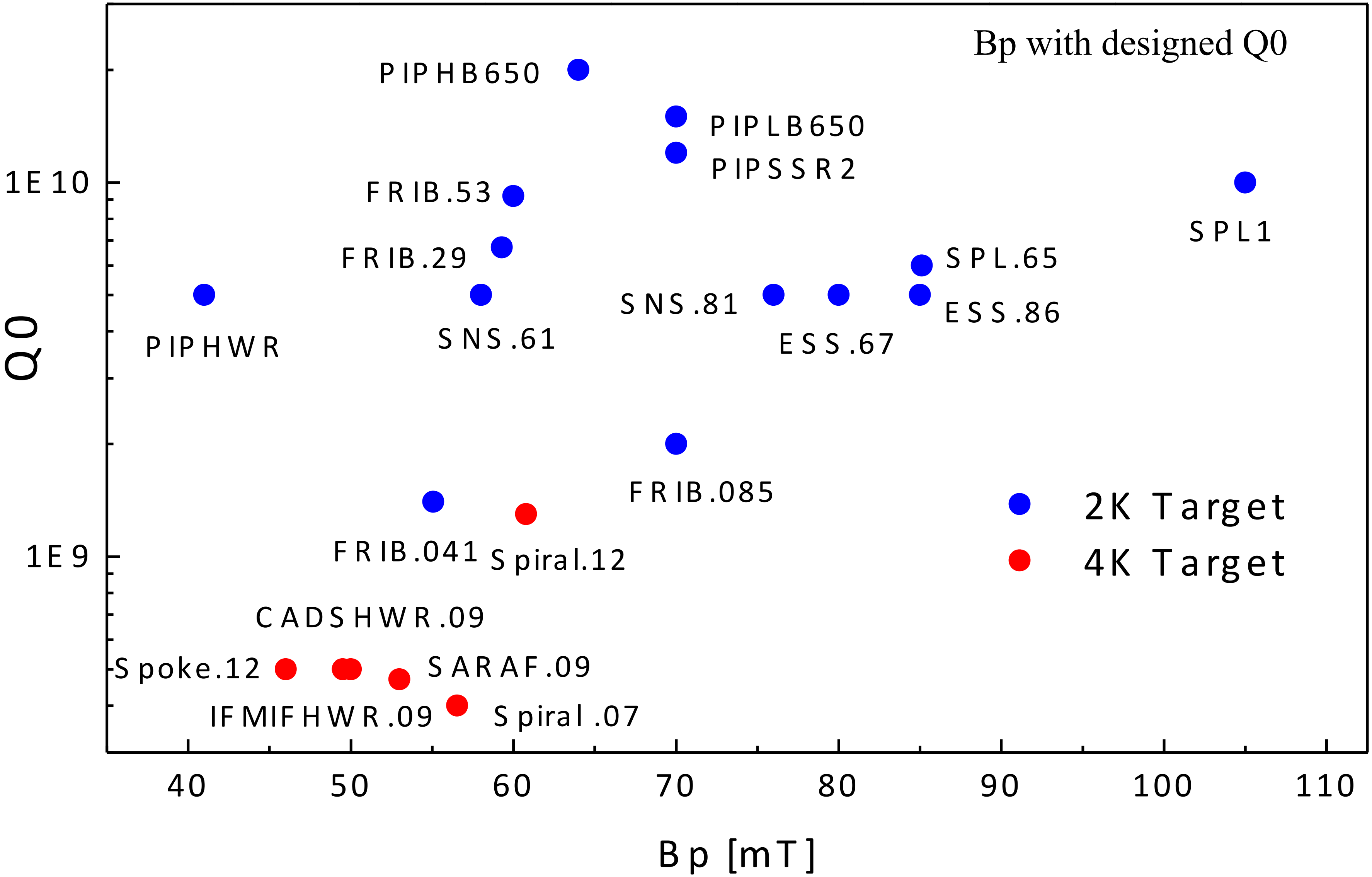


- The study on HOM focuses on elliptical cavity only. How about low beta structure? Is it issue when the beam beam intensity is quite high?

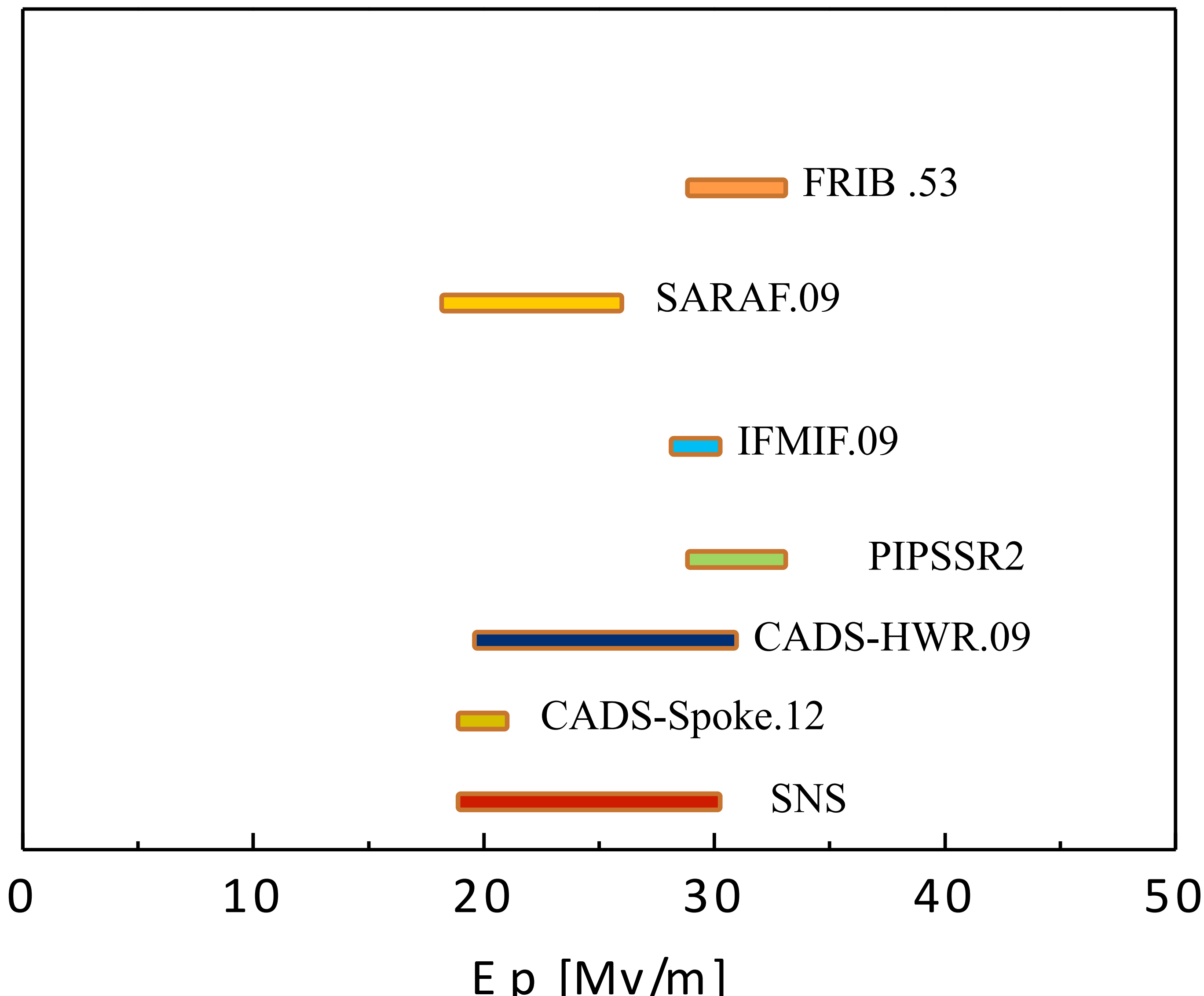
Designed Q0 and Tested Q0 at Designed Epk



Q0 vs Bpk in Various Projects



FE Onset in Various Cavities



Summary

- For limit of Epeak and gradient, elliptical cavity like ESS mainly concerns the limits of power coupler.
- Limit of Epeak for a low beta cavities seems Bpeak or FE, almost all cavities quench finally. Max Bpeak is around 100 mT, far away from critical field. FE onset almost in the range of 20 to 30 MV/m.
- Q slop at middle field is general for a low beta structure, it seems limit of the Q0 but Epeak. High Q0 cavity can not go higher gradient.
- No consideration is obviously related high intensity especially for a low beta cavity.
- High-Order Modes for 10 mA beam → "to damp, or not to damp?" SNS leans towards a negative conclusion. How about low beta structure like QWR and Spoke?
- Limits related with high intensity, SNS may give us an answer in presentation of Sang-Ho Kim on Tuesday morning WG6.

Acknowledgement

- Sang-Ho Kim, SNS
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- Slava Yakovlev, PIP II/ProjectX/PIXE
- Alban Mosnier, IFMIF
- Steve Malloy, ESS
- Slides for SARAF are from internet
- And others in WG6

Thanks for your attention!