APPLICATIONS OF SPOKE CAVITIES

Jean Delayen

Center for Accelerator Science
Old Dominion University
and
Thomas Jefferson National Accelerator Facility

Outline

- **Historical background**
- **Basic geometries**
- **Survey of properties**
- **Some applications**
- **Summary**

History

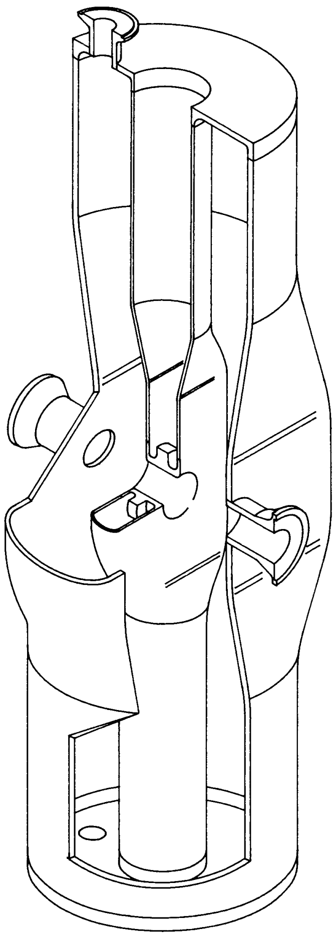
- The spoke cavity and the coaxial half-wave cavity were developed at ANL in the late 1980s with support from the Strategic Defense Initiative Program
  - ~10's mA, ~100 MeV, p and D, low emittance
  - Proposed for IFMIF
  - Proposed for ADS

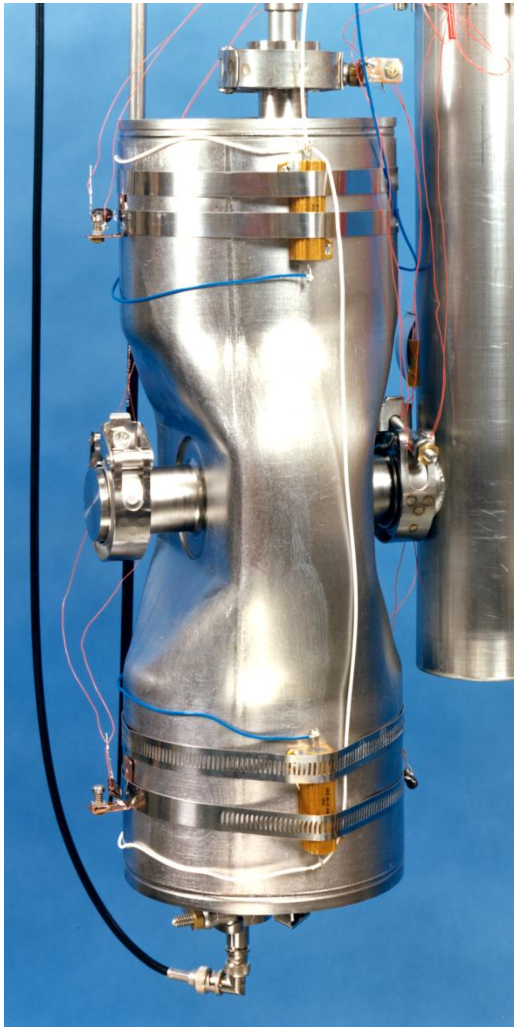
- Support from SDI stopped in 1992, and in 1994 for IFMIF and ADS.

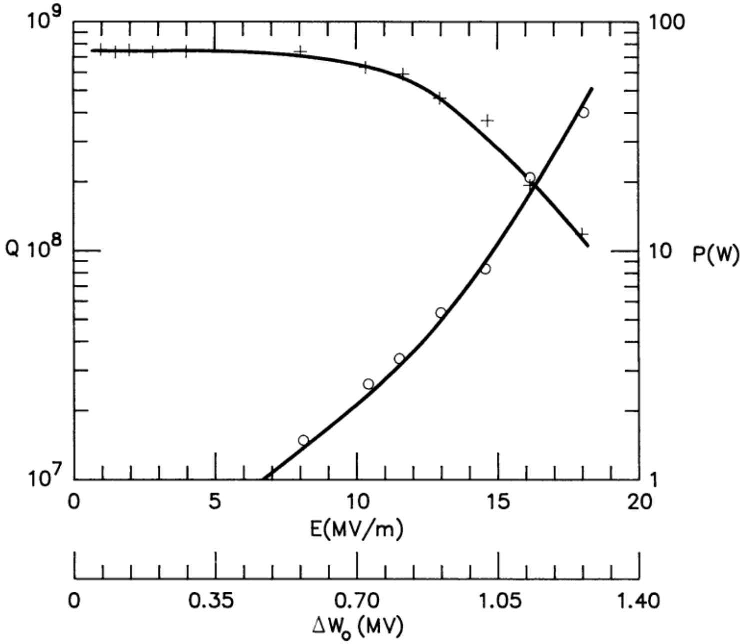
- Interest in those geometries was revived in the late 1990s at ANL for RIA and other laboratories for many other high-current ion accelerators

- The spoke geometry is now the geometry of choice in the medium velocity region and is being developed in many laboratories worldwide

352 MHz, β=0.12 Coaxial Half-Wave (1989)

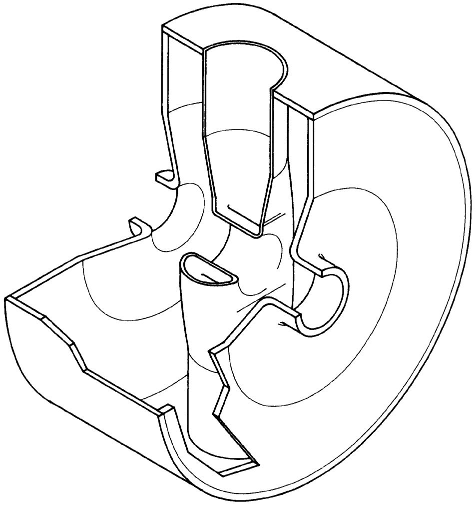


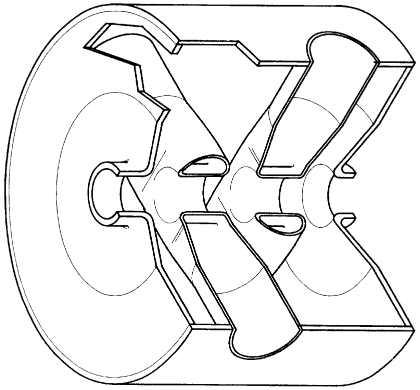


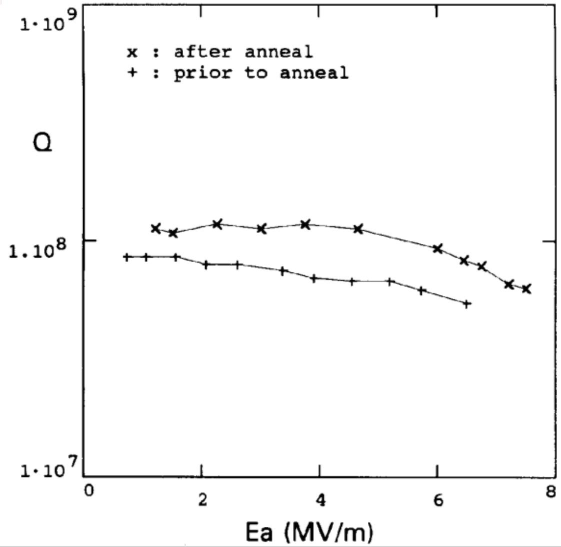


ANL

850 MHz, β=0.3 Spoke (1990)



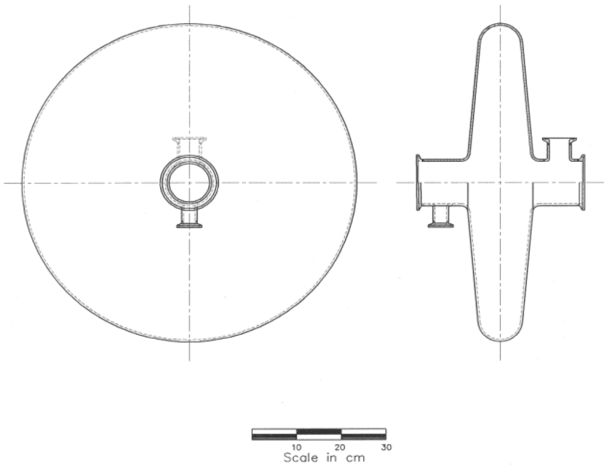




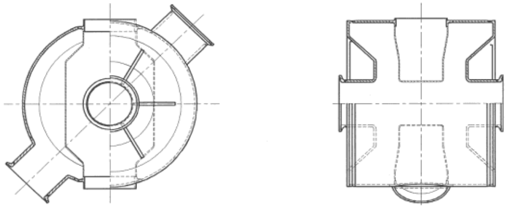
ANL

Features of Spoke Cavities

- **Small Size**
  - **About half of TM cavity of same frequency**
- Allows low frequency at reasonable size
  - Possibility of 4.2 K operation
  - High longitudinal acceptance
- Fewer number of cells
  - Wider velocity acceptance

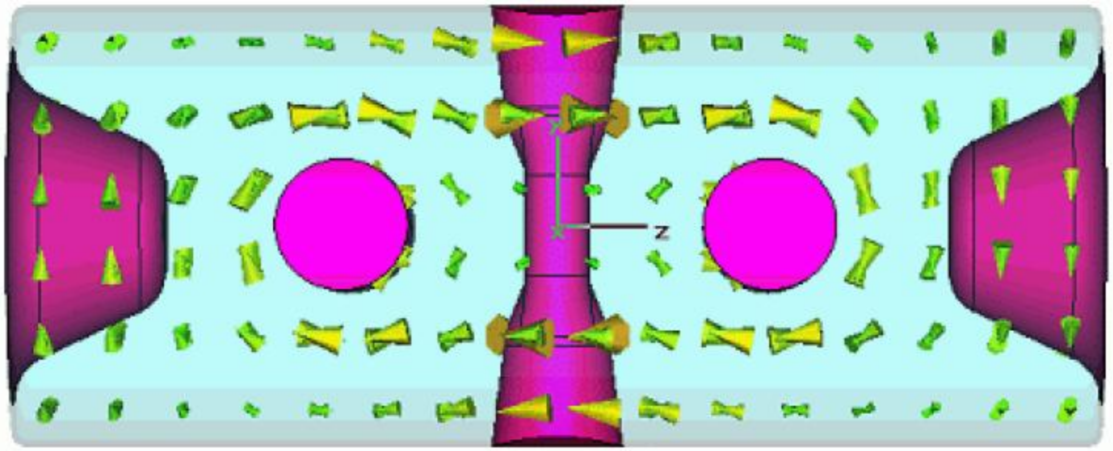


350 MHz, β= 0.45



Features of Spoke Cavities

- **Strong cell-to-cell coupling in multi-spoke**
  - All the cells are linked by the magnetic field
  - Field profile robust with respect to manufacturing inaccuracy
  - No need for field flatness tuning
  - Closest mode well separated



Magnetic Field Profile: 352 MHz, β=0.48 (FZJ)

Features of Spoke Cavities

- **Accelerating mode has lowest frequency**
  - No lower-order mode
  - Easier HOM damping

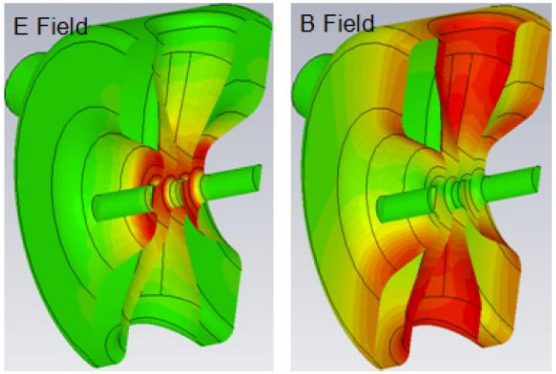
	3-spoke		9-cell (TESLA)	
Mode #	**Freq. (MHz)**	**Δf/f % of f_{ACC}**	**Freq. (MHz)**	**Δf/f % of f_{ACC}**
1	345		1275.6	1.7
2	365	5.7	1277.6	1.6
3	401	14	1280.7	1.4
4	442	28	1284.5	1.1
5	482	40	1288.5	0.8
6	519.7	51	1292.4	0.5
7	520.2	51	1295.5	0.2
8	534	55	1297.6	0.05
9	619	79	1298.3	
10	679	97		

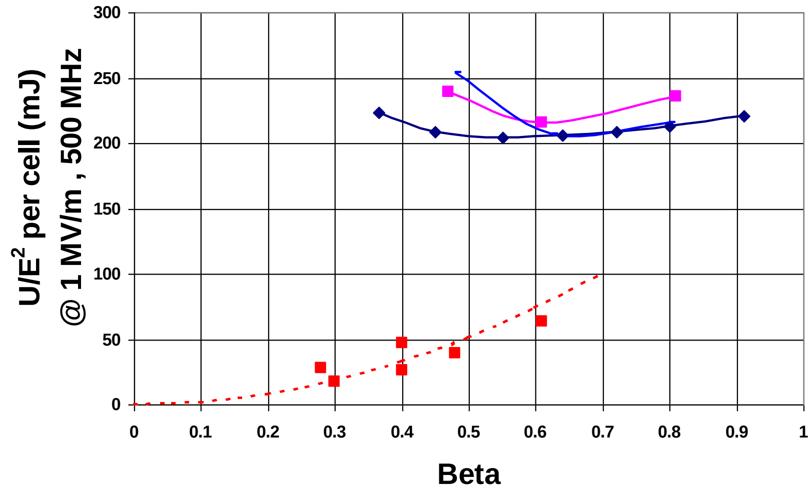
M. Kelly (ANL)

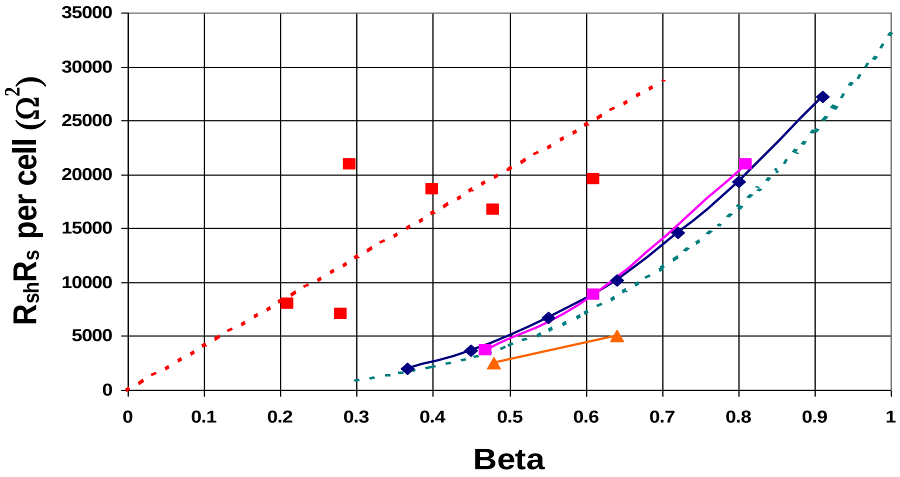
Features of Spoke Cavities

- **Electromagnetic energy concentrated near the spokes**
  - Low energy content
  - High shunt impedance
  - Low surface field on the outer surfaces
    - Couplers (fundamental and HOM) can be located on outer conductor
    - Couplers do not use beamline space

325 MHz, β=0.17 (FNAL)

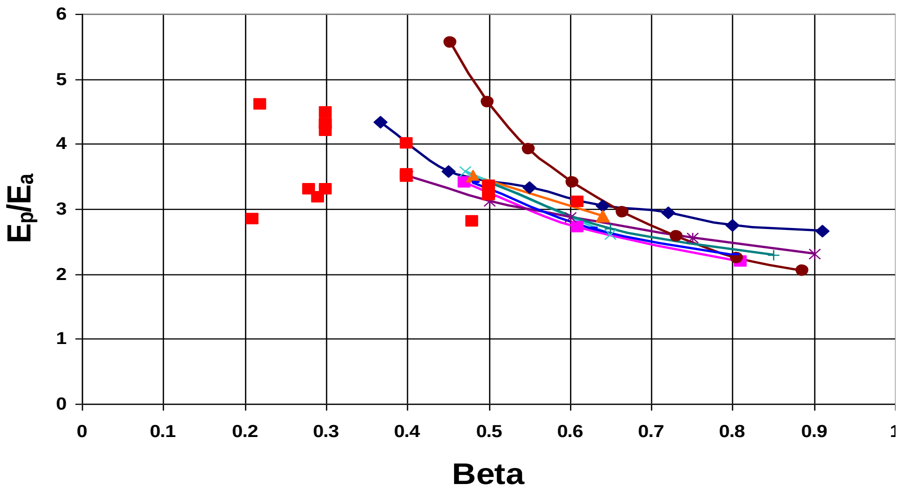


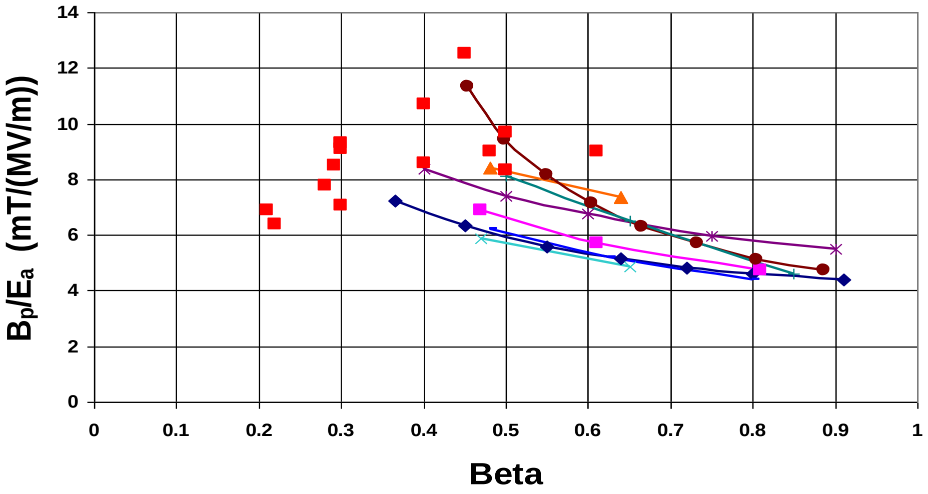




Features of Spoke Cavities

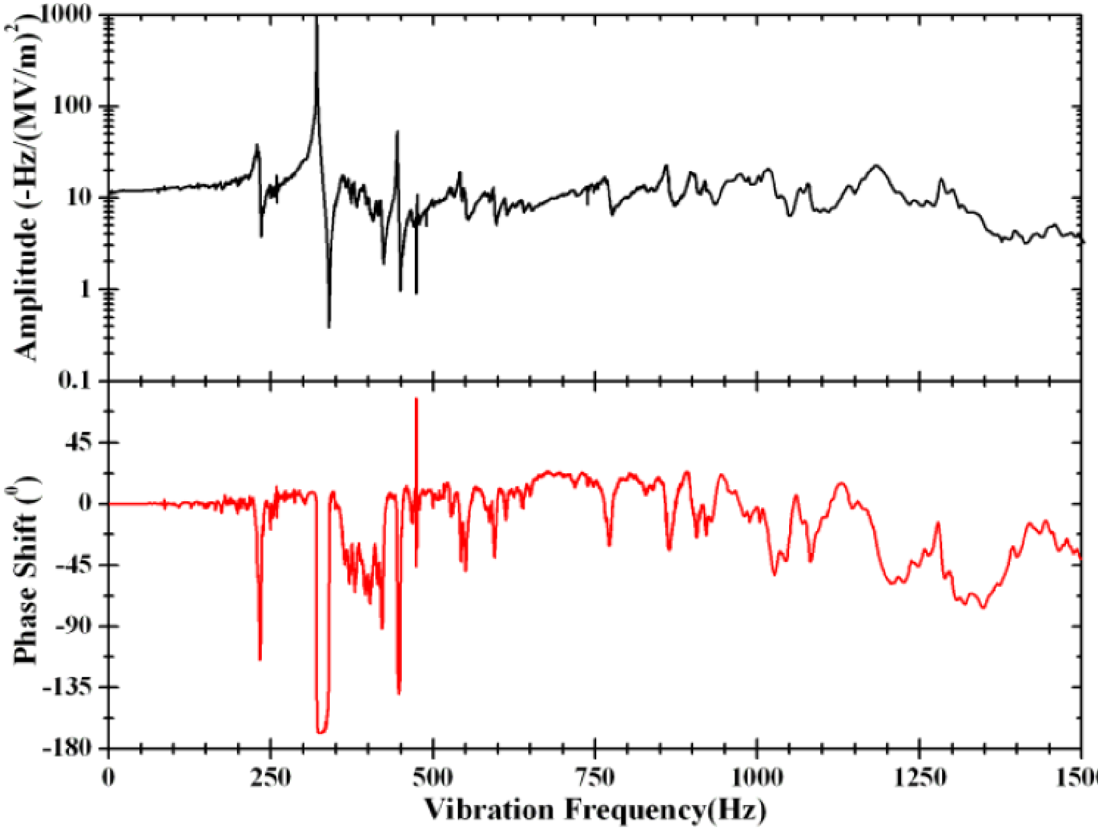
- **Peak surface electromagnetic fields**
  - At high β, peak surface electromagnetic fields tend to be higher for spoke cavities
  - Difference may be small at constant real estate gradient
  - Spoke cavities will usually be used in applications where gradients are modest (cw and/or high-current)





Features of Spoke Cavities

- **Few mechanical modes, none at low frequency**



Lorentz Transfer Function: 345 MHz, β=0.5, triple-spoke (Z. Conway, ANL)

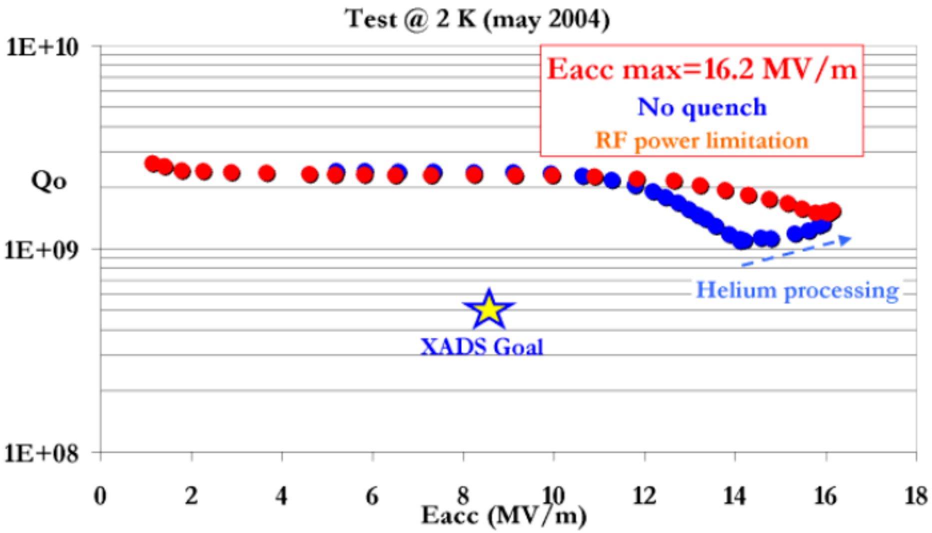
Spoke Cavities Worldwide

Labs	Spoke-type	Frequency [MHz]	Geometrical /Optimal betas	Eacc max [MV/m]		Epk [MV/m]		Bpk [mT]		Voltage gain [MV]		Limitation	
				4.2 K	2 K	4.2 K	2 K	4.2 K	2 K	4.2 K	2 K	4.2 K	2 K
IPN Orsay	Single	352	0.15/0.20	4.8		32.0		69.0		0.8		Quench	
	Single	352	0.35/0.36	8.1	10.6	38.0	49.5	104.0	134.0	2.5	3.2	Power	Quench
ANL	Single	855	0.28/0.28	4.4		24.0		56.0		0.3		Power	
	Single	345	0.29/0.29	8.8	8.6	40.0	39.0	106.0	105.0	2.2	2.2	Quench	Quench
	Single	345	0.40/0.40	7.0	7.3	44.0	46.0	117.0	123.0	2.4	2.6	Quench	Quench
	Double	345	0.40/0.40	8.6	8.8	40.0	41.0	79.0	81.0	4.5	4.6	Quench	Quench
	Triple	345	0.50/0.50	7.7	7.7	28.0	28.0	88.0	88.0	6.7	6.7	Quench	Quench
	Triple	345	0.63/0.63	7.9	9.5	31.0	37.0	95.0	114.0	8.7	10.4	Quench	Quench
LANL	Single	350	0.175/0.21 EZ01	7.5	7.5	38.0	38.0	100.0	100.0	1.4	1.4	Quench	Quench
	Single	350	0.175/0.21 EZ02	7.2	7.5	37.0	38.0	96.0	100.0	1.3	1.4	Quench	Quench
Juelich	Triple	760	0.2/0.2	8.6	12.2	42.8	60.6	87.2	123.3	1.4	1.9	Quench	Power
	Triple	352	0.48/0.48										
Fermilab	Single	325	0.21/0.21 SSR1-01	12.0	9.1	43.7	33.0	69.7	52.6	2.4	1.8	Time out	Power limit
	Single	325	0.21/0.21 SSR1-02	16.7	22.0	60.8	80.2	96.8	127.7	3.4	4.5	Quench	Quench
	Single	325	0.21/0.21 SSR1-03										
	Single	325	0.21/0.21 SSR1-04										

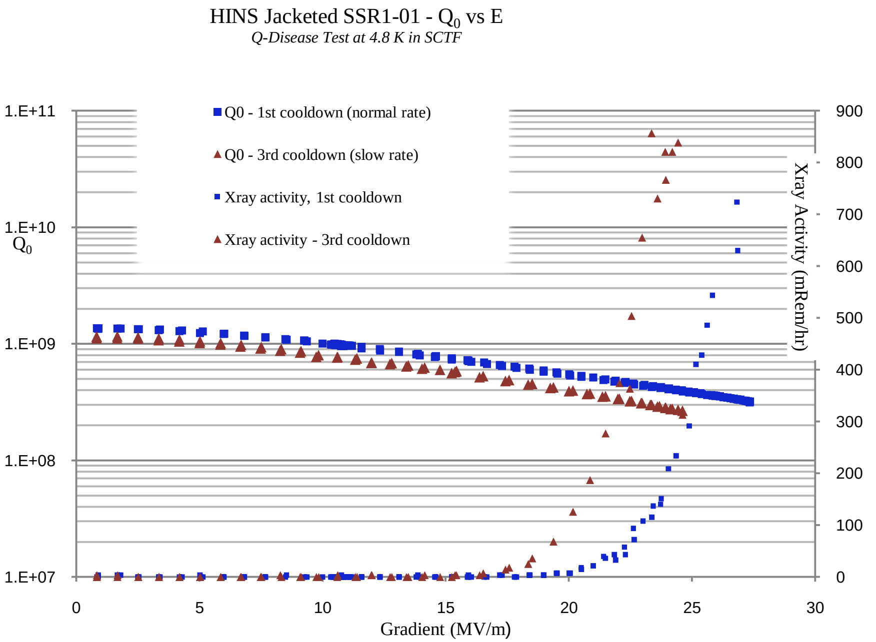
G. Olry, IPN Orsay

Experimental Results

- **Achieved gradients (single spoke)**



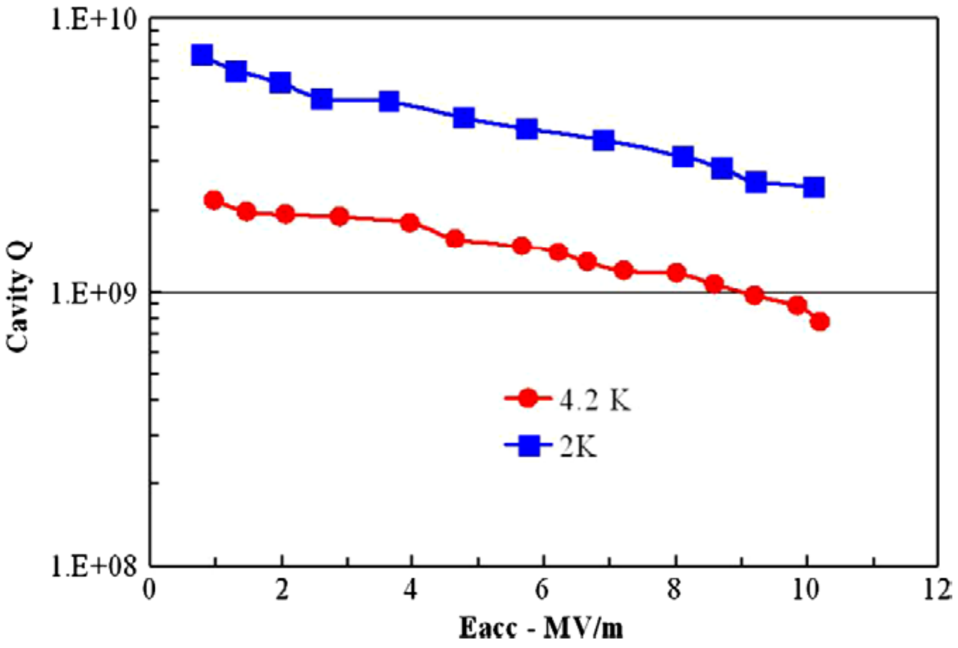
352 MHz, β=0.35 (IPN Orsay)



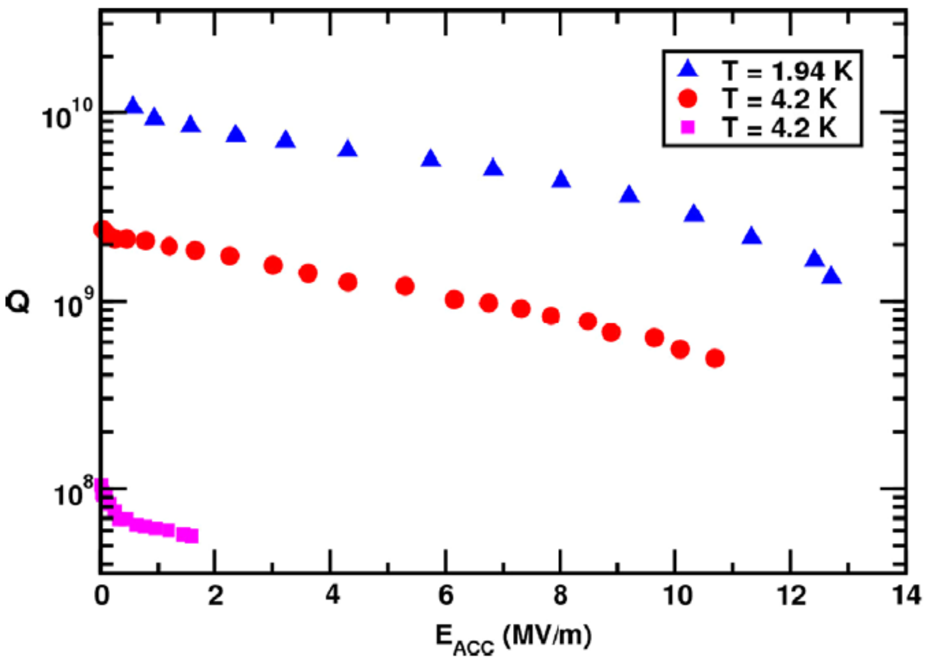
325 MHz, β=0.22 (FNAL)

Experimental Results

- **Achieved gradients (triple spoke)**



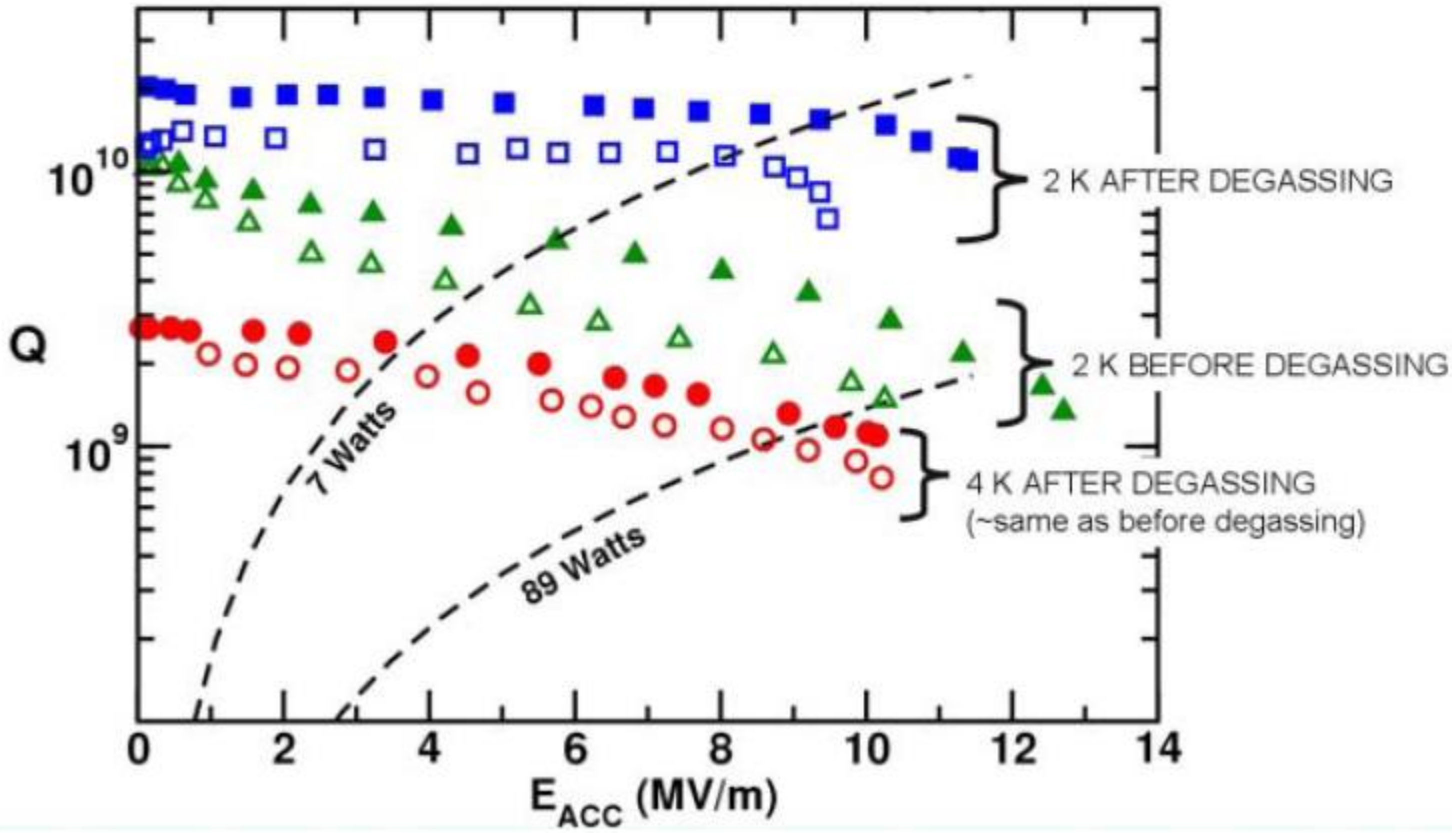
345 MHz, β=0.5 (ANL)



345 MHz, β=0.63 (ANL)

Experimental Results

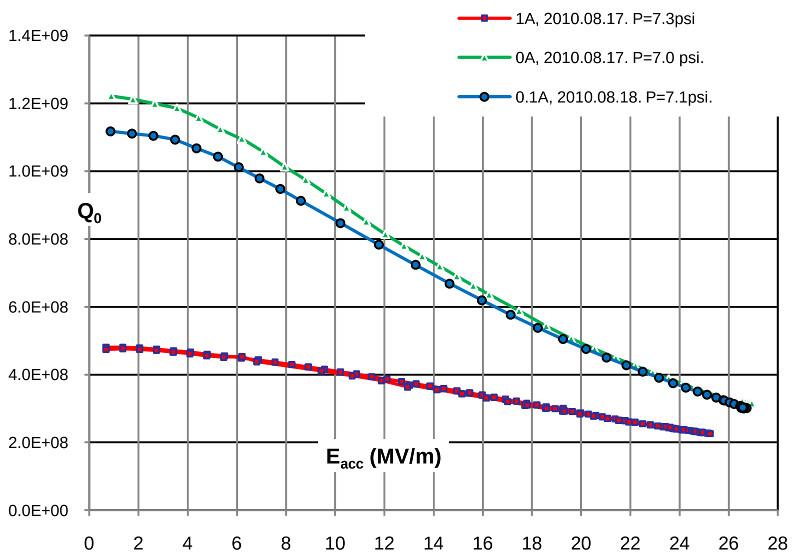
- **Hydrogen degassing at 600^{0}C (triple spoke)**

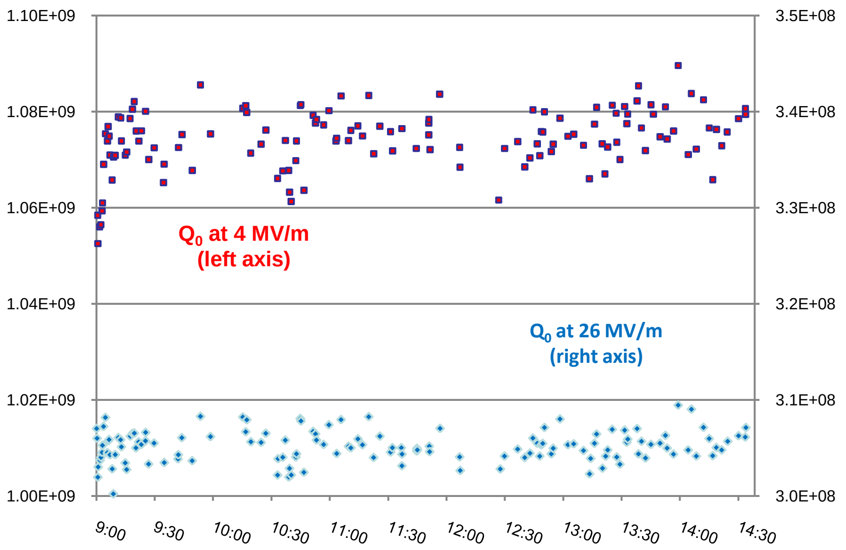


Open symbols: 345 MHz, β=0.5 (ANL) **Closed symbols: 345 MHz, β=0.63 (ANL)**

Experimental Results

- **Sensitivity to magnetic field**





Q_0 degradation due to magnetic field captured during cooling down. (1 A (red) is 2 G field)

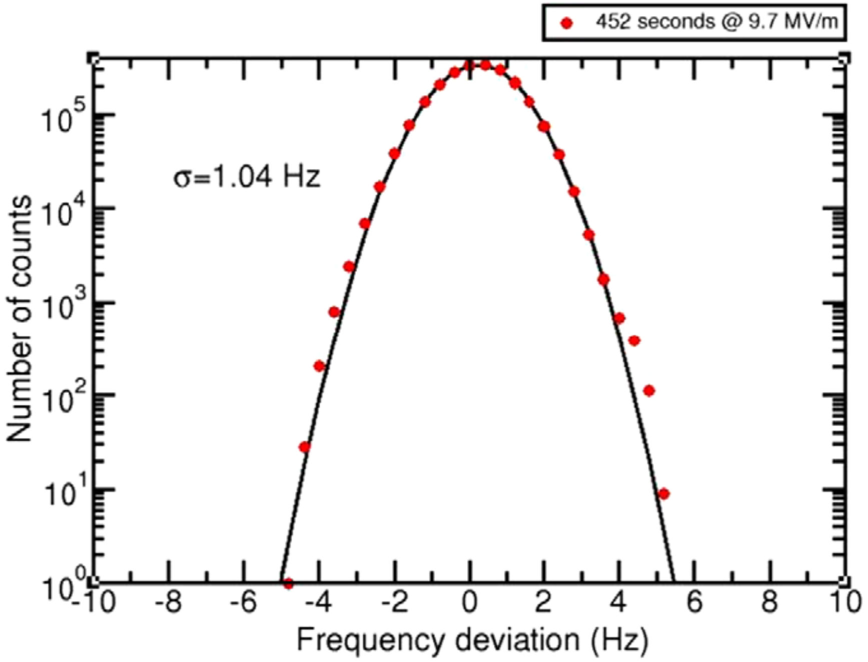
Q_0 at low and high E_{acc} during period of multiple quenches in presence of 8-10 G magnetic field

325 MHz, β=0.22 (FNAL)

Experimental Results

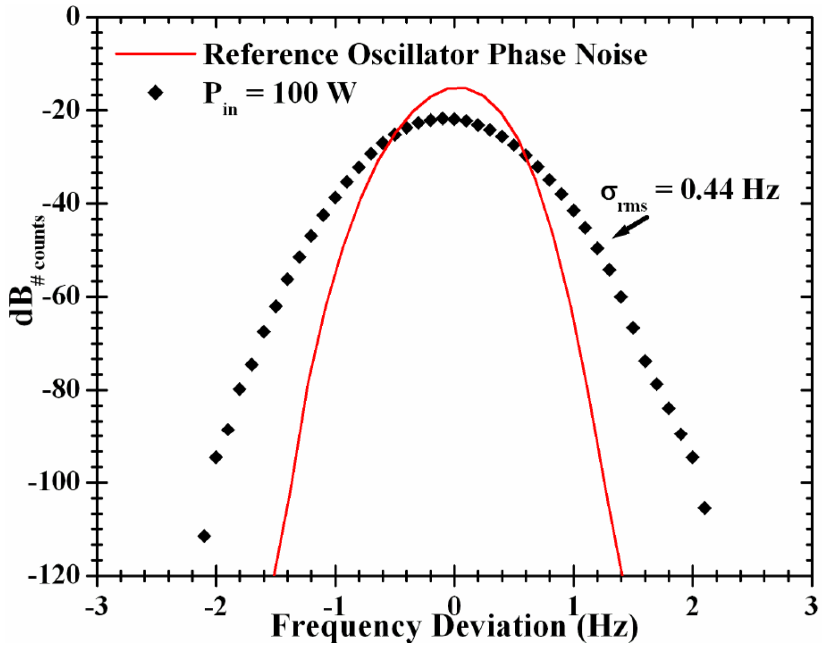
- **Microphonics and sensitivity to He pressure**

Before optimization



df/dp= -9.6 Hz/mbar

After optimization

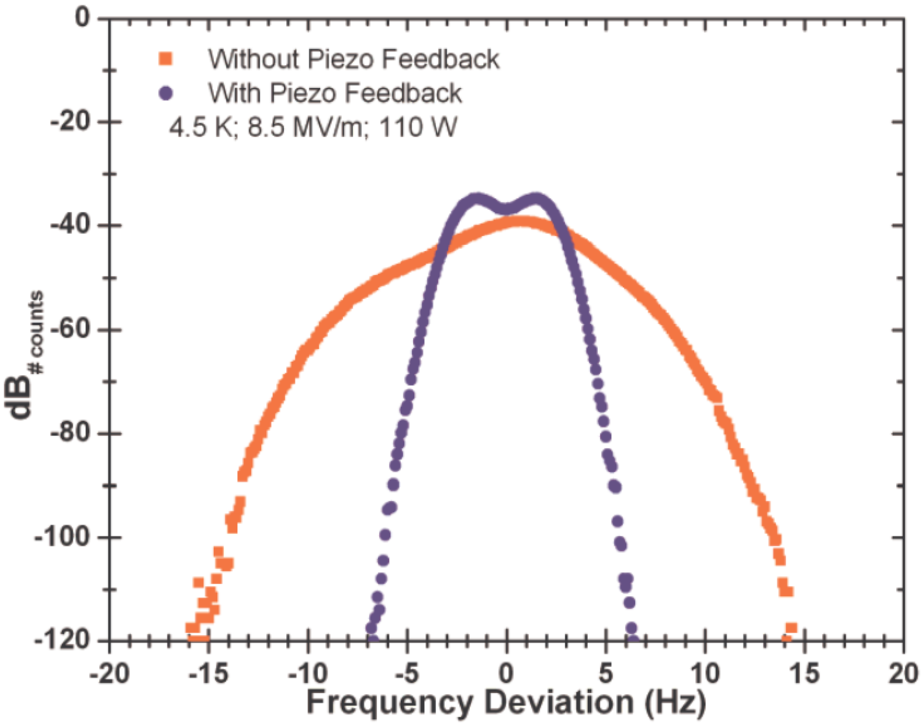


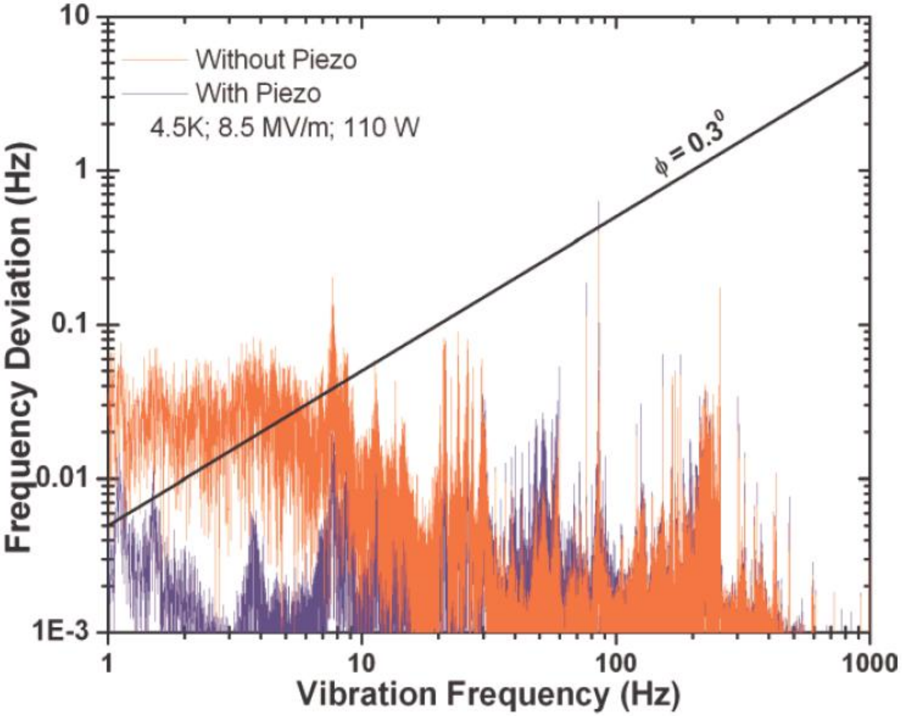
df/dp= -0.4 Hz/mbar

345 MHz, β=0.5, triple-spoke (Z. Conway, ANL)

Experimental Results

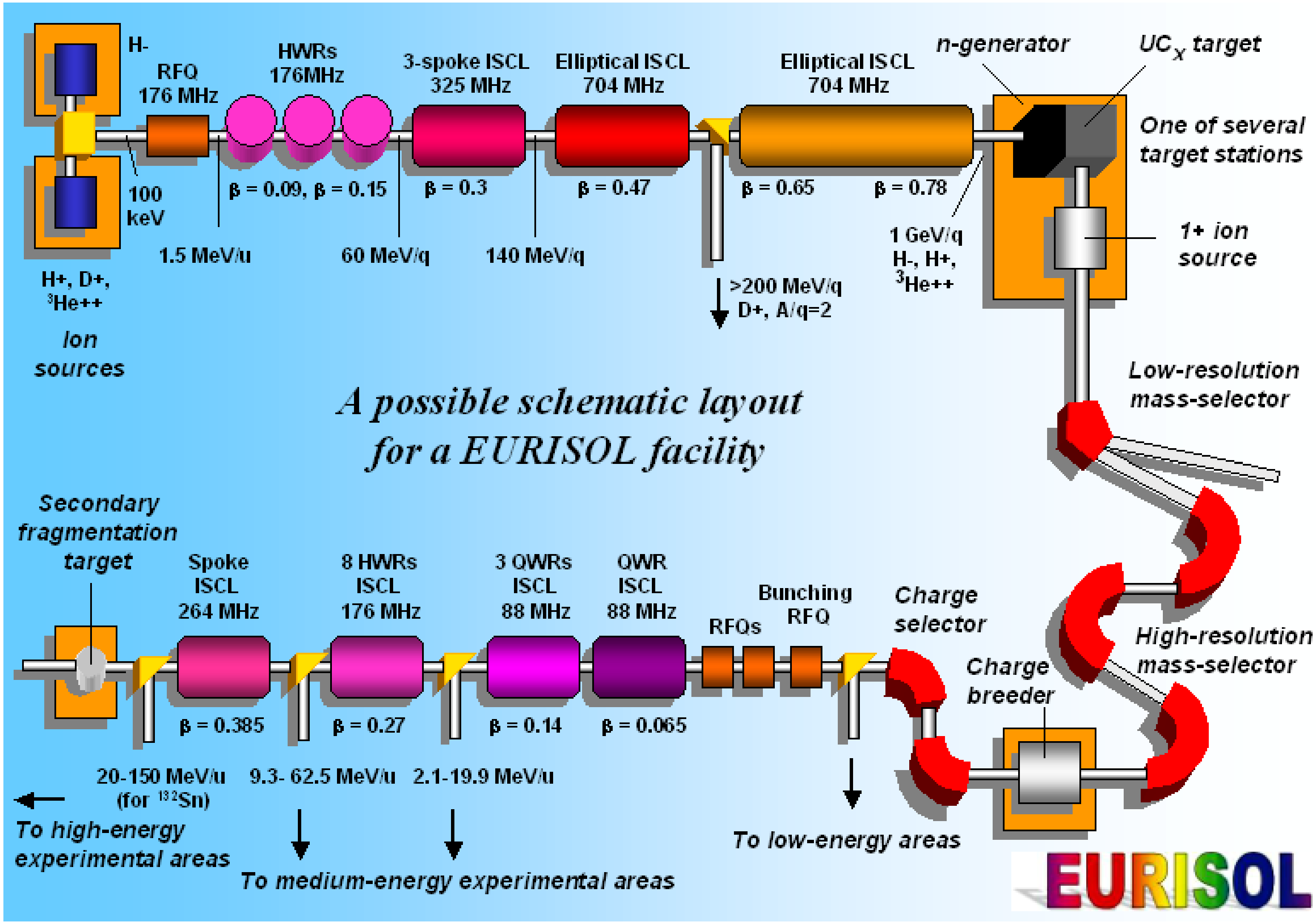
- **Microphonics control with piezo tuners**





345 MHz, β=0.5 Triple spoke (ANL)
Low frequency microphonics intentionally enhanced by connecting the cavity to forced-flow system

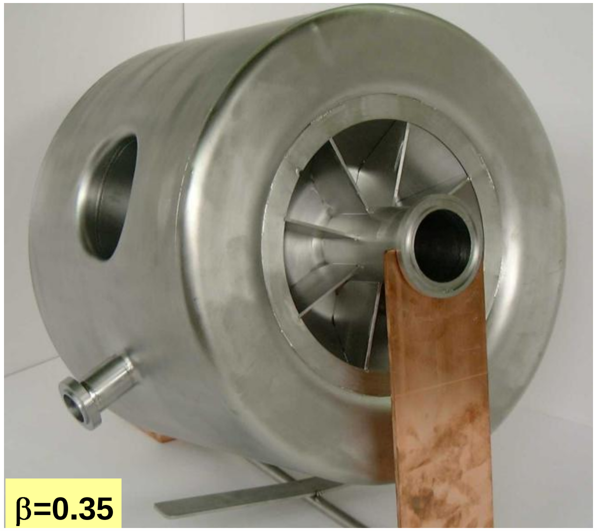
EURISOL

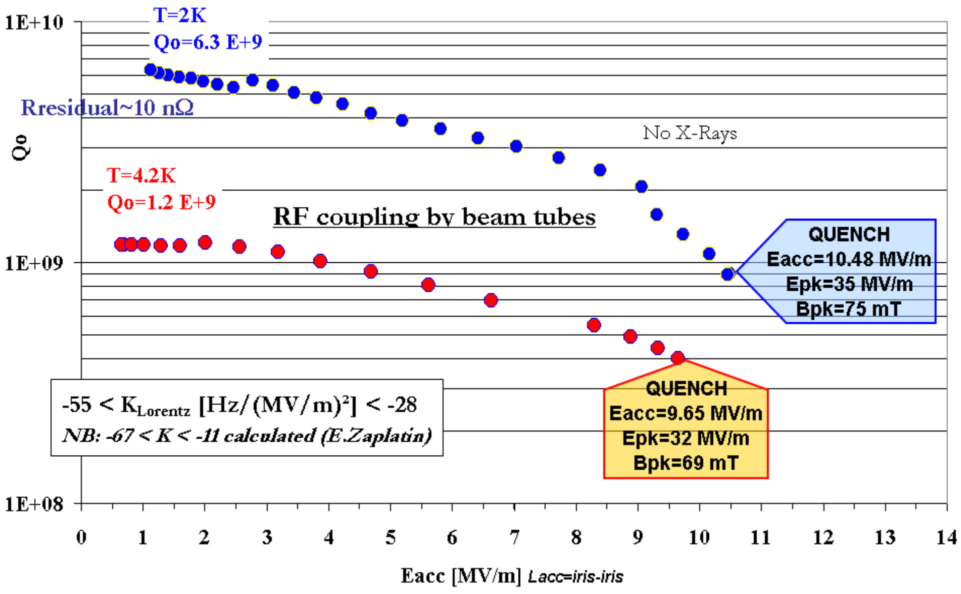


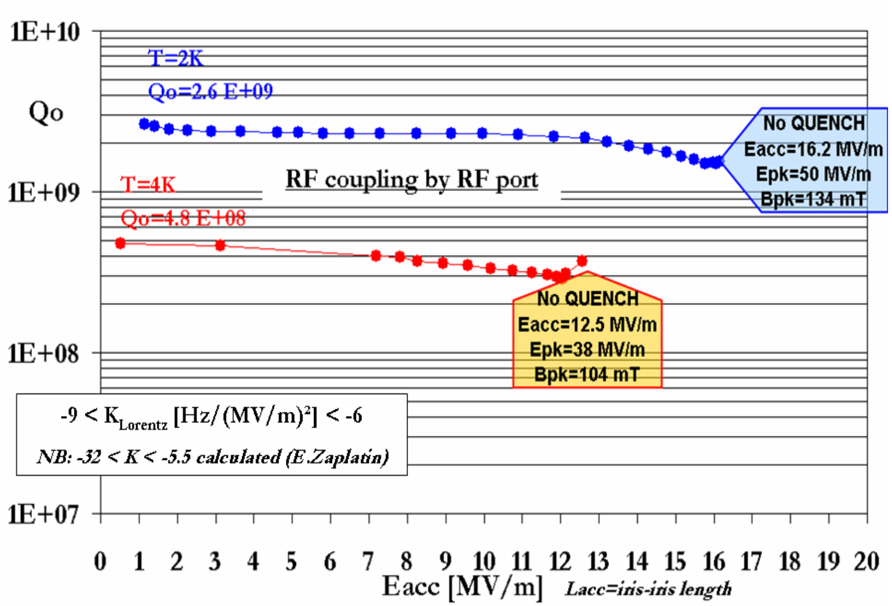
H-
RFQ 176 MHz
HWRs 176MHz
3-spoke ISCL 325 MHz
Elliptical ISCL 704 MHz
Elliptical ISCL 704 MHz
n-generator
UCx target
One of several target stations
100 keV
β = 0.09, β = 0.15
β = 0.3
β = 0.47
β = 0.65
β = 0.78
1.5 MeV/u
60 MeV/q
140 MeV/q
1 GeV/q H-, H+, 3He++
1+ ion source
>200 MeV/q D+, A/q=2
H+, D+, 3He++
Ion sources
Low-resolution mass-selector
A possible schematic layout for a EURISOL facility
Secondary fragmentation target
Spoke ISCL 264 MHz
8 HWRs ISCL 176 MHz
3 QWRs ISCL 88 MHz
QWR ISCL 88 MHz
RFQs
Bunching RFQ
Charge selector
High-resolution mass-selector
Charge breeder
β = 0.385
β = 0.27
β = 0.14
β = 0.065
20-150 MeV/u (for 132Sn)
9.3- 62.5 MeV/u
2.1-19.9 MeV/u
To high-energy experimental areas
To medium-energy experimental areas
To low-energy areas
EURISOL

EURISOL

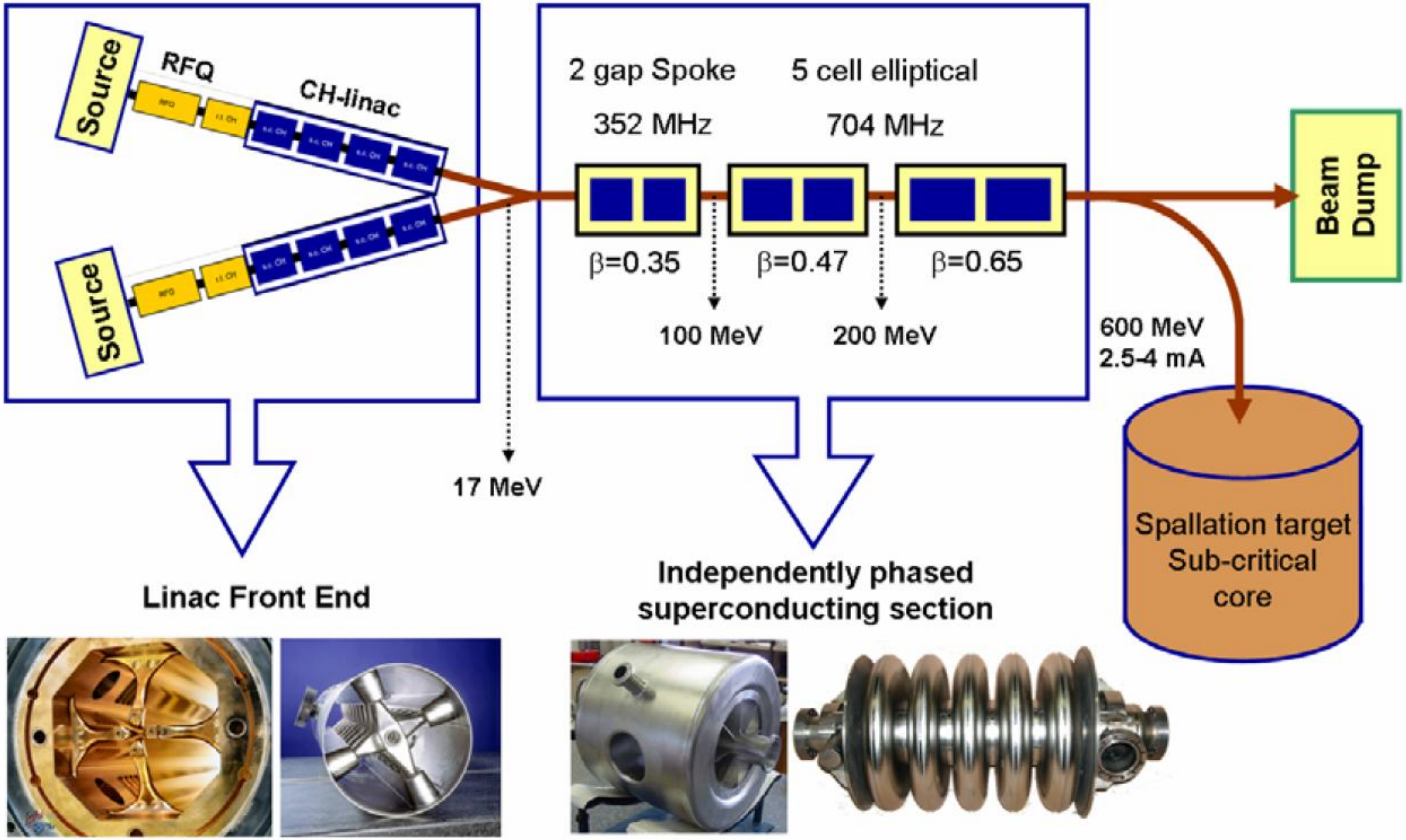
IPN Orsay





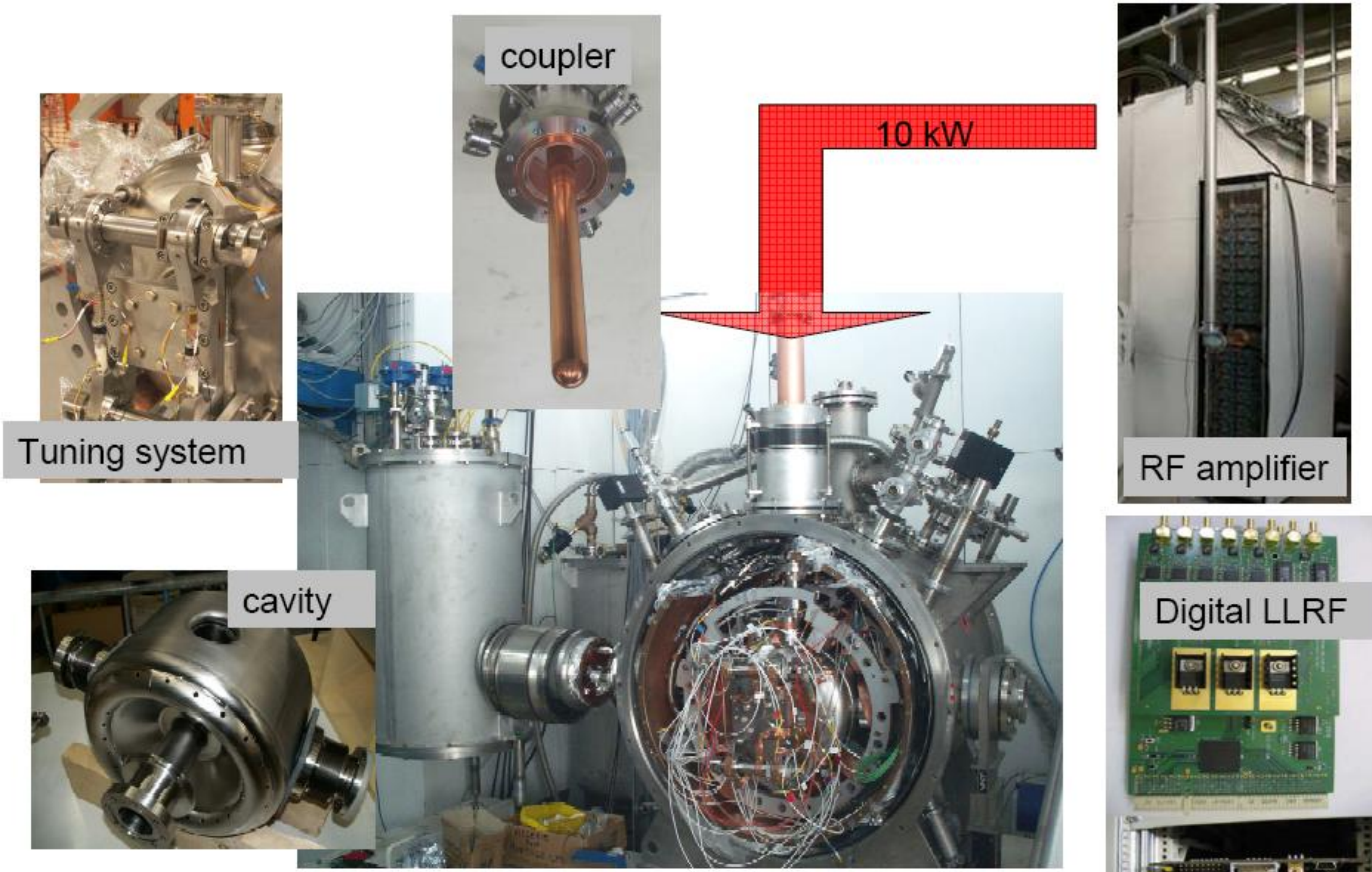


EUROTRANS



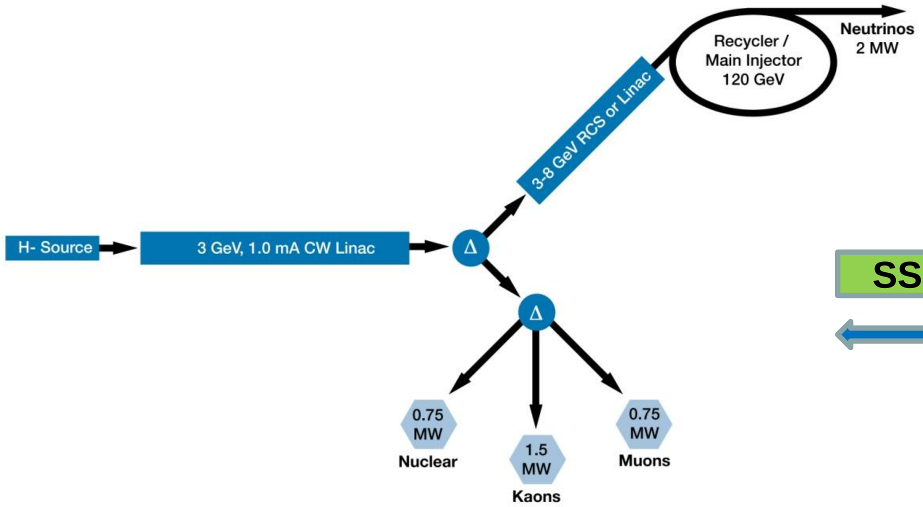
Source
RFQ
CH-linac
Source
2 gap Spoke
352 MHz
5 cell elliptical
704 MHz
β=0.35
β=0.47
β=0.65
100 MeV
200 MeV
17 MeV
600 MeV
2.5-4 mA
Beam Dump
Spallation target
Sub-critical
core
Linac Front End
Independently phased
superconducting section

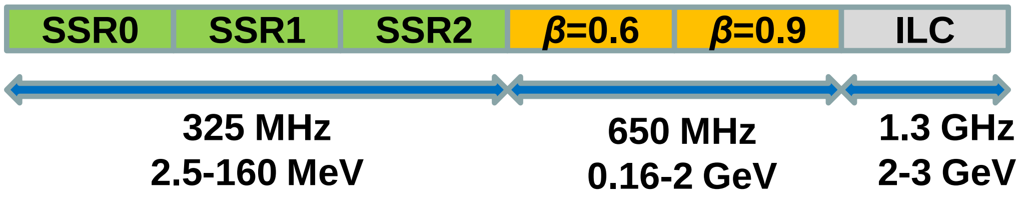
Spoke Cavity Integrated Tests (Orsay)



Sebastien Bousson, 4th meeting ESSS reference group

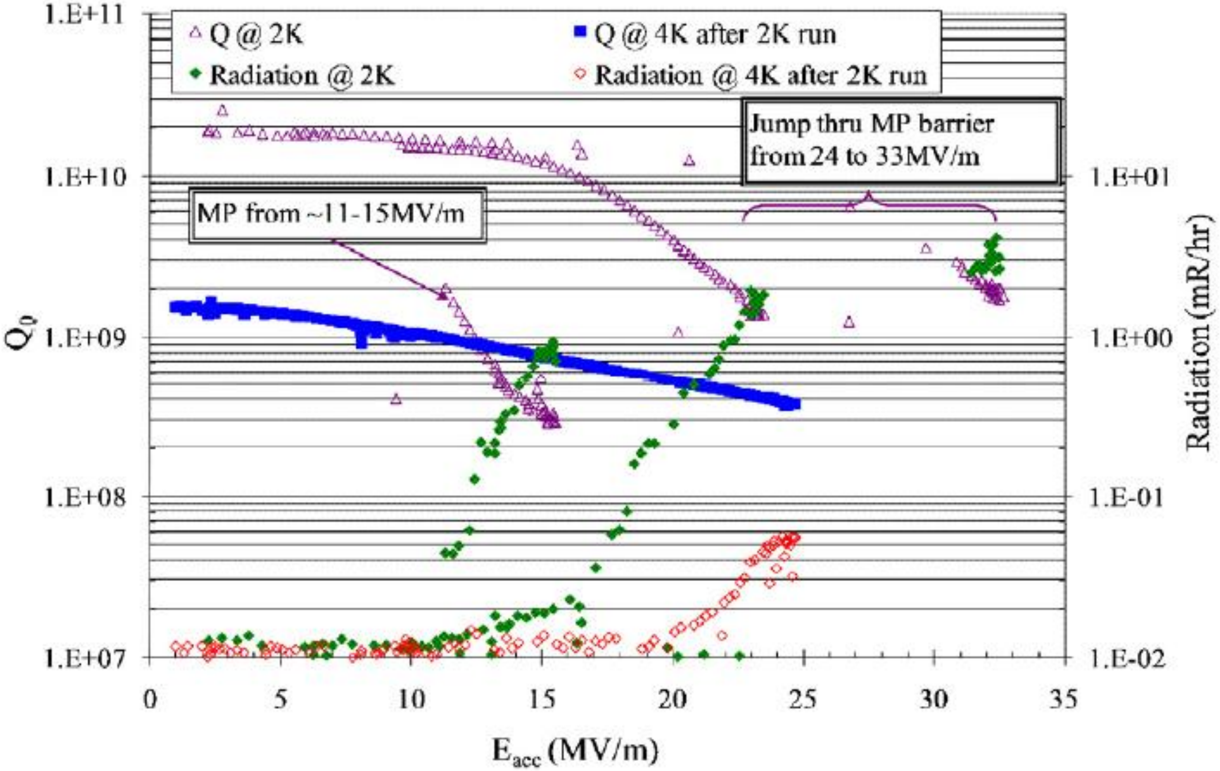
Fermilab Project X

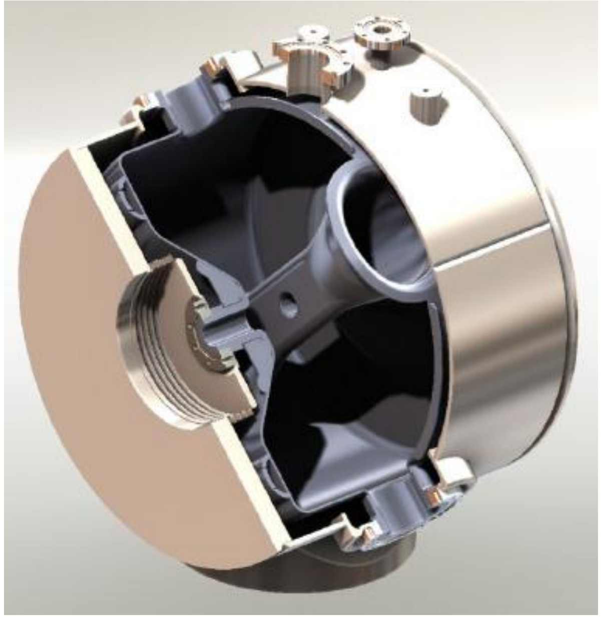




Section	Freq	Energy (MeV)	Cav/mag/CM	Type
SSR0 (β_G=0.11)	325	2.5-10	26 /26/1	SSR, solenoid
SSR1 (β_G=0.22)	325	10-32	18 /18/ 2	SSR, solenoid
SSR2 (β_G=0.4)	325	32-160	44 /24/ 4	SSR, solenoid
LB 650 (β_G=0.61)	650	160-520	42 /21/ 7	5-cell elliptical, doublet
HB 650 (β_G=0.9)	650	520-2000	96 /12/12	5-cell elliptical, doublet
ILC 1.3 (β_G=1.0)	1300	2000-3000	64 / 8/ 8	9-cell elliptical, quad

Fermilab Project X

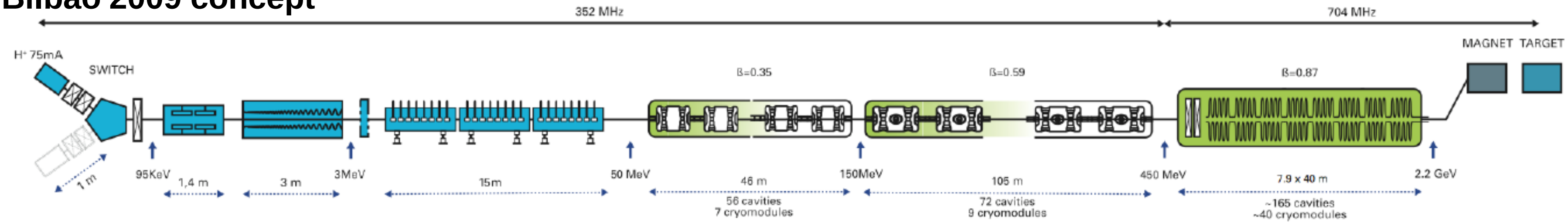


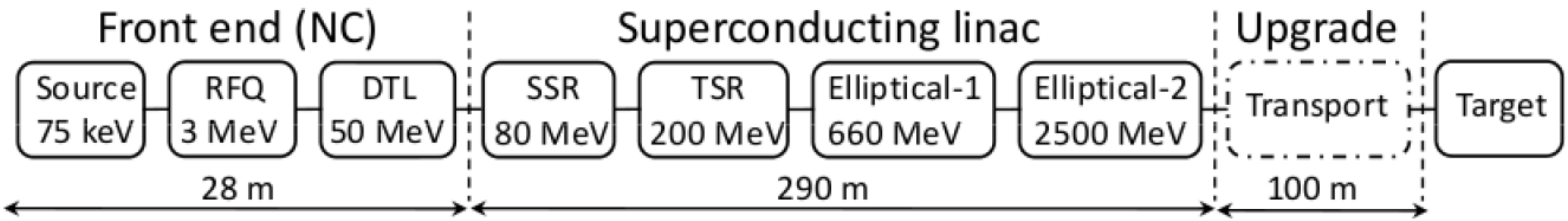


325 MHz, β=0.22

European Spallation Source

Bilbao 2009 concept





Scandinavia 2009 concept

System	T [K]	Energy [MeV]	Freq. [MHz]	β v/c	Length [m]
Source	300	0.075	–	–	2.5
LEBT	300	–	–	–	1.1
RFQ	300	3	352.2	–	4.0
MEBT	300	–	352.2	–	1.1
DTL	300	50	352.2	–	19.2
SSR	4	80	352.2	0.35	23.3
TSR	4	200	352.2	0.50	48.8
Ellipt-1	2	660	704.4	0.65	61.7
Ellipt-2	2	2500	704.4	0.92	154.0

European Spallation Source

2010 concept

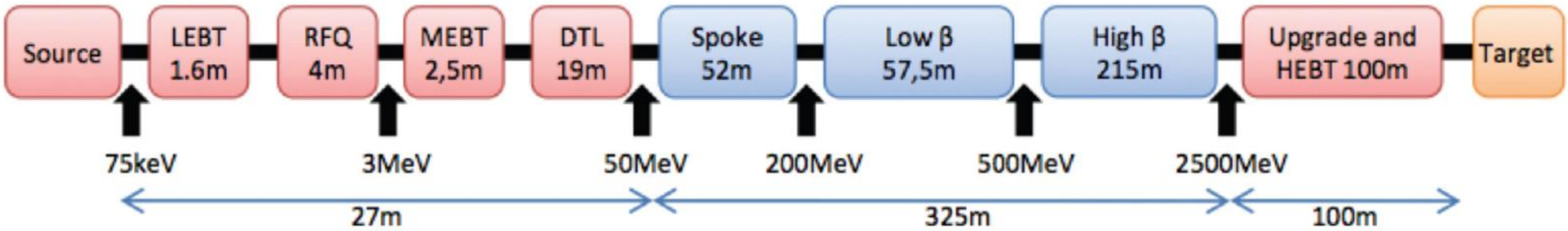


Table 1: Primary ESSS performance parameters in the long pulse conceptual design. There is no accumulator ring.

INPUT		**Nominal**	**Upgrade**
Average beam power	[MW]	5.0	7.5
Macro-pulse length	[ms]	2.0	2.0
Pulse repetition rate	[Hz]	20	20
Proton kinetic energy	[GeV]	2.5	2.5
Peak coupler power	[MW]	1.0	1.0
Beam loss rate	[W/m]	< 1.0	< 1.0
OUTPUT			
Duty factor		0.04	0.04
Ave. pulse current	[mA]	50	75
Ion source current	[mA]	60	90
Total linac length	[m]	418	418

System	Energy MeV	Freq. MHz	β_{Geo}	No. of modules	Length m
Source	0.075	–	–	–	2.5
LEBT	0.075	–	–	–	1.6
RFQ	3	352.2	–	1	4.0
MEBT	3	352.2	–	–	2.5
DTL	50	352.2	–	3	19
Spokes	200	352.2	0.45	14	52
Low β	500	704.4	0.63	10	57
High β	2500	704.4	0.75	19 (21*)	215

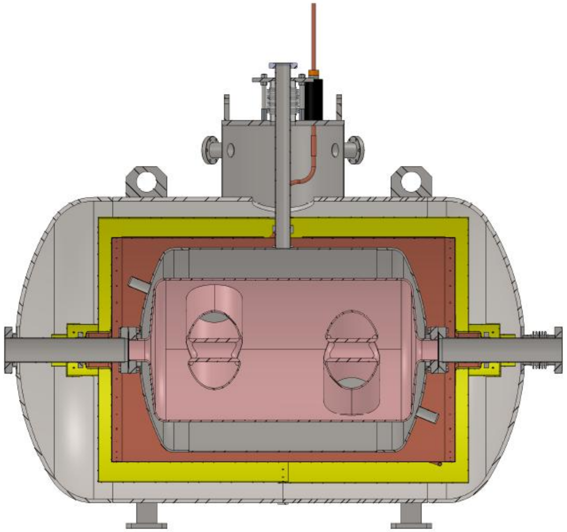
*High power LINAC

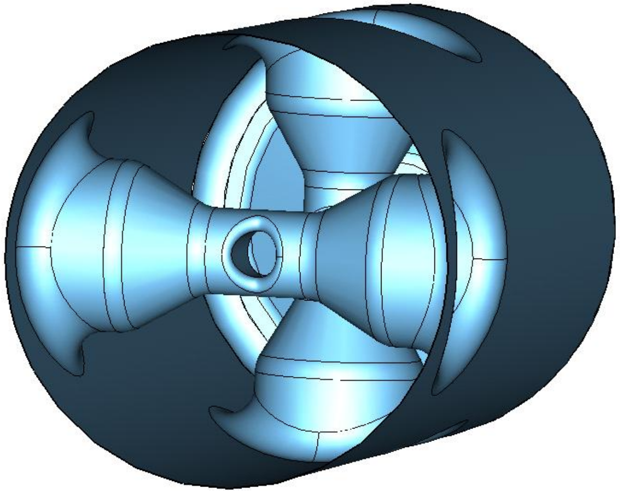
How High Can We Go with β_g in Spoke Cavities?

- What are their high-order modes properties?
  - Spectrum
  - Impedances
  - Beam stability issues
- Is there a place for spoke cavities in high-β high-current applications?
  - FELs, ERLs
  - Higher order modes extraction

How High Can We Go with β_g in Spoke Cavities?

- **Activities in this area are finally starting**
  - **ODU-JLab collaboration to develop a 352 MHz, β=0.8 double-spoke cavity**
  - **ODU-Niowave collaboration to develop a 500 MHz, β=1 double-spoke cavity. Plan is to test it with the Naval Postgraduate School superconducting gun**





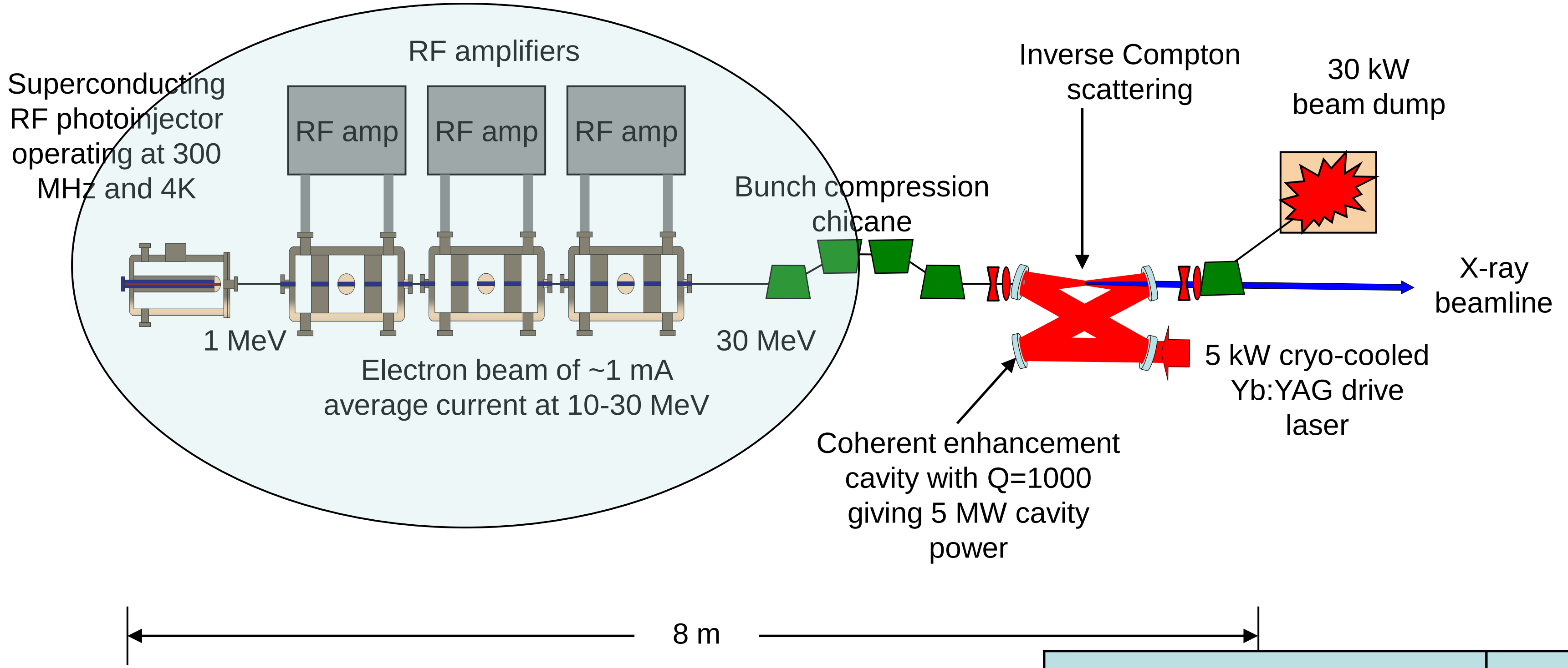
Compact Light Sources

- Most existing SRF cavities require or benefit from 2K operation
  - Too complex for a University or small institution-based accelerator
  - Cryogenics is a strong cost driver for compact SRF linacs

- Spoke cavities can operate at lower frequency
  - Lower frequency allows operation at 4K
  - No sub-atmospheric cryogenic system
  - Significant reduction in complexity

- Similar designs for accelerating low-velocity ions are close to desired specifications

Compact Light Sources



MIT CUBIX proposal
Multi-institutional collaboration

SRF Linac Parameters	
Energy gain [MeV]	25
RF frequency [MHz]	352
Average current [mA]	1
Operating temperature [K]	4.2
RF power [kW]	30

Parting Thoughts

- The first spoke cavity was developed 20 years ago
- The spoke geometry has many attractive features
- Many prototypes have been, or are being, developed in many institutions
  - 300 to 850 MHz
  - β from <0.2 to 1
- They are not yet in use in any operating machine
- The main argument against using them seems to be that they are not in use yet
- Many thanks to all the colleagues who have provided information