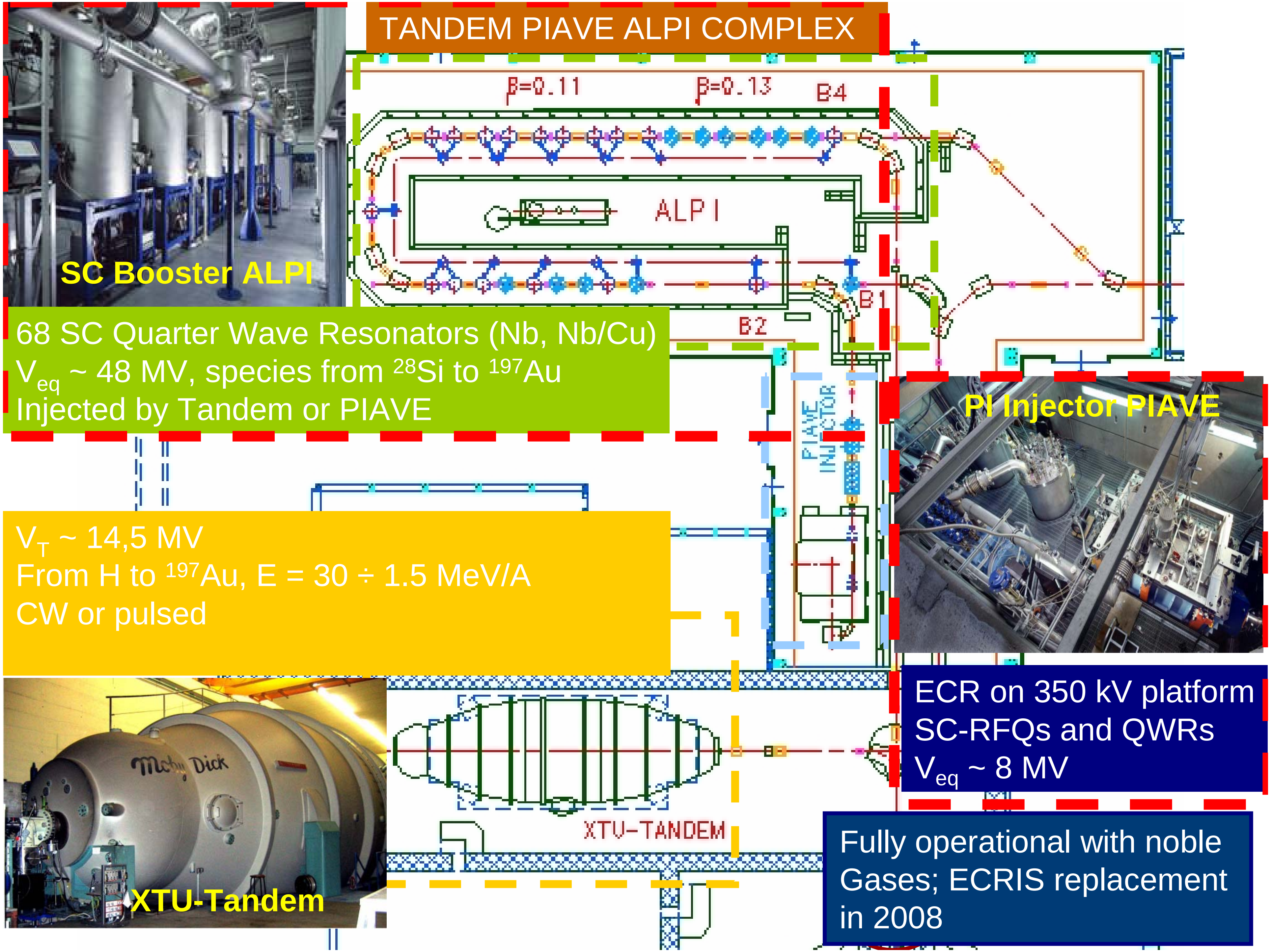
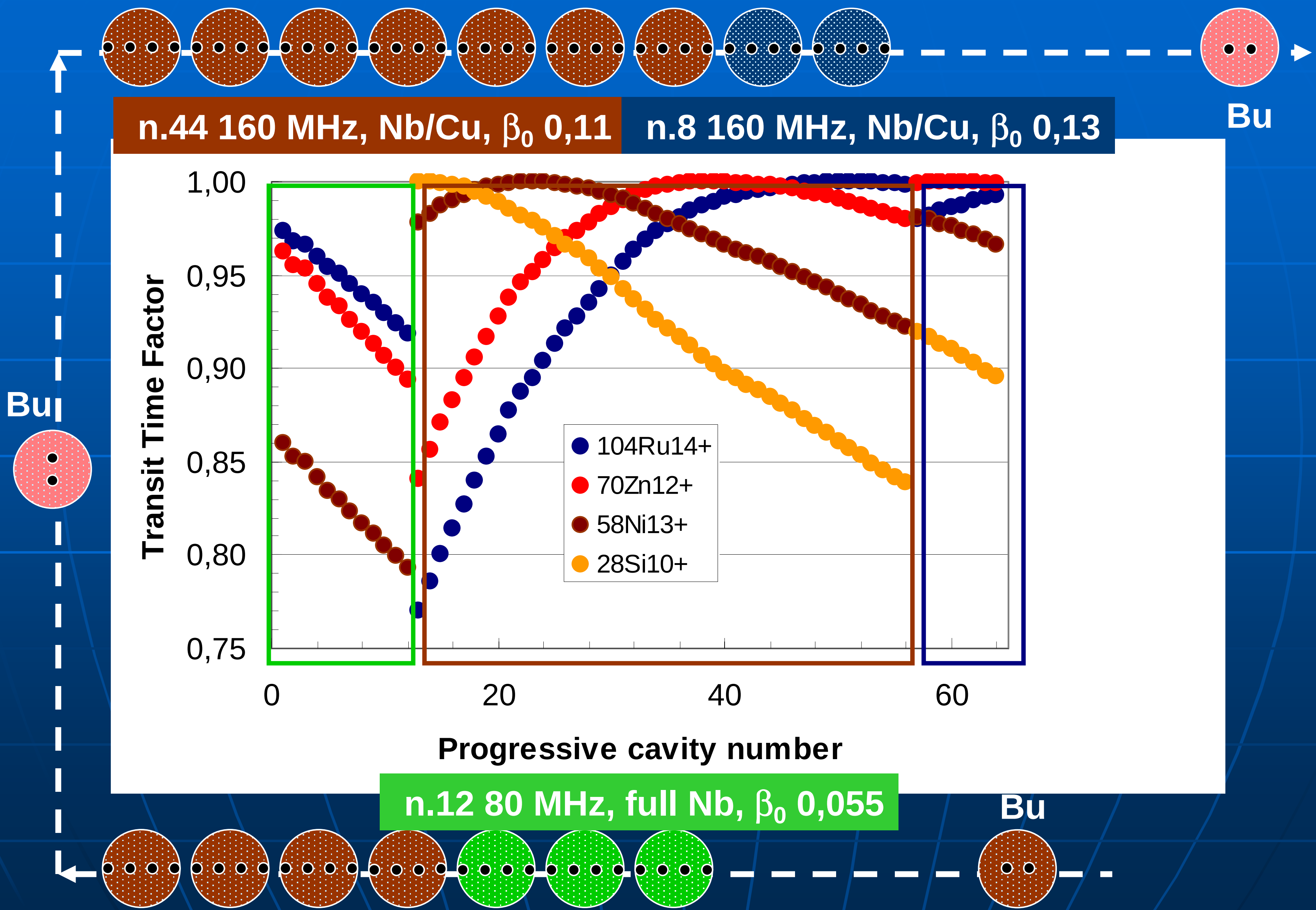
ALPI QWR and S-RFQ operating experience

Giovanni Bisoffi, INFN-LNL

1. Machine status
2. QWR & S-RFQ performance and operation issues
3. On-going improvements


TANDEM PIAVE ALPI COMPLEX
SC Booster ALPI
β=0.11
β=0.13
B4
ALPI
B1
B2
68 SC Quarter Wave Resonators (Nb, Nb/Cu)
V_{eq} ~ 48 MV, species from ^{28}Si to ^{197}Au
Injected by Tandem or PIAVE
PIAVE INJECTOR
PI Injector PIAVE
V_T ~ 14,5 MV
From H to ^{197}Au, E = 30 ÷ 1.5 MeV/A
CW or pulsed
ECR on 350 kV platform
SC-RFQs and QWRs
V_{eq} ~ 8 MV
XTU-TANDEM
Moby Dick
XTU-Tandem
Fully operational with noble Gases; ECRIS replacement in 2008

U-shaped linac with 3 QWR β_0 sections



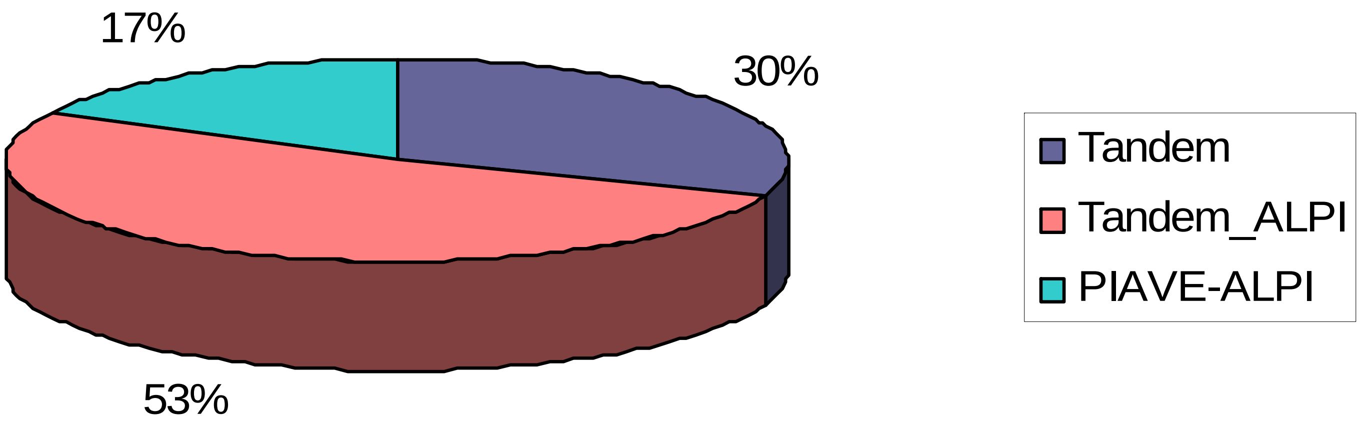
TANDEM-ALPI REPRESENTATIVE BEAMS

Beam	E [MeV] - (1 foil)	Beam current [pnA]	E [MeV] - (2 foils)
^{12}C	240	10	250
^{16}O	290	30	320
^{32}S	440	18	550
^{48}Ca	440	1	610
^{58}Ni	540	5	750
^{65}Cu	530	2	750
^{74}Ge	515	2	800
^{82}Se	560	1	800
^{90}Zr	530	1.5	
^{104}Ru	550	1	

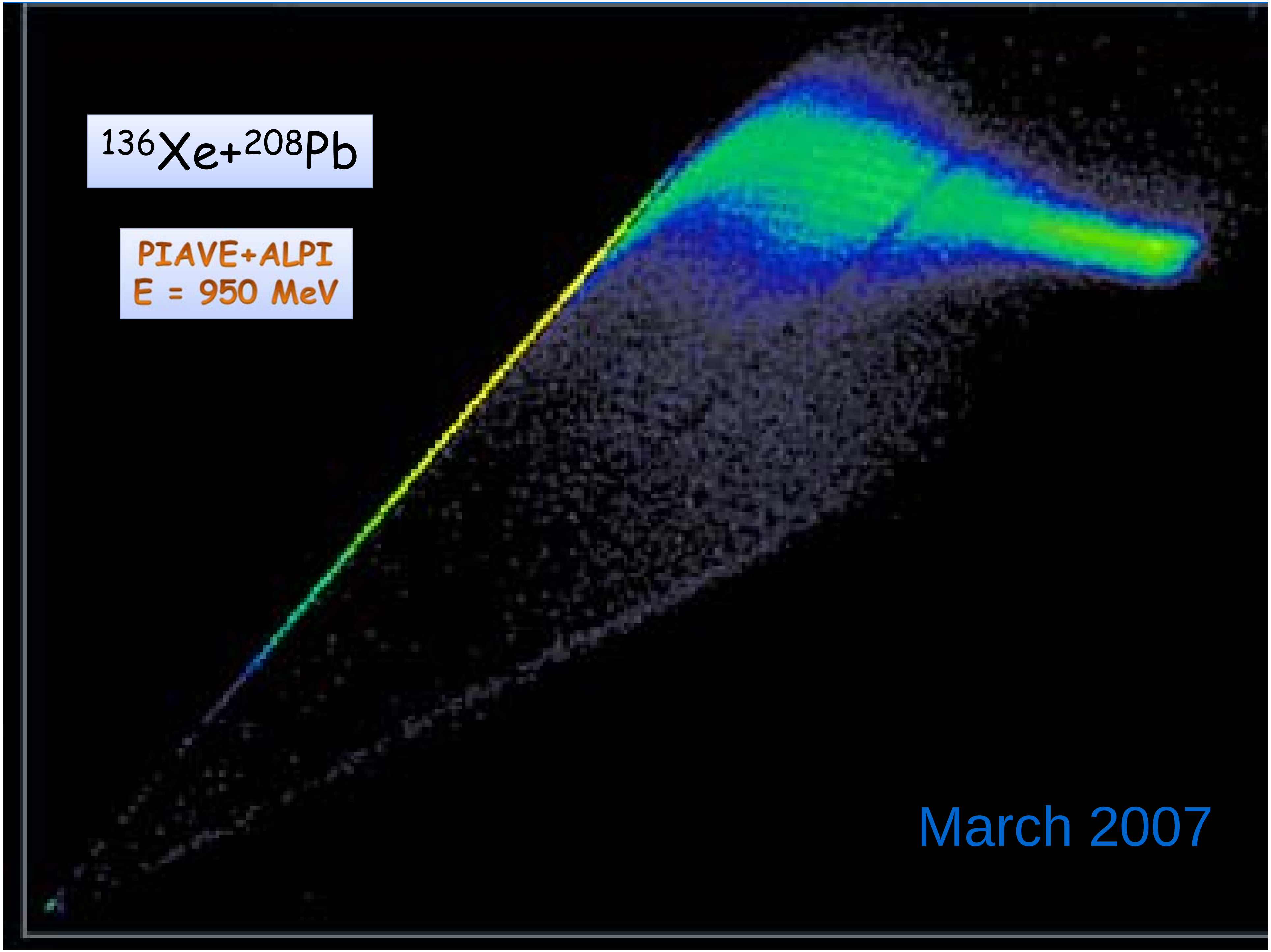
PIAVE-ALPI BEAMS

Beam	E [MeV]	Beam Current [pnA]
$^{22}Ne^{4+}$	150	10
$^{40}Ar^{9+}$	350	$4 \div 10$
$^{84}Kr^{15+}$	600	$5 \div 10$
$^{132}Xe^{18+}$	720	$5 \div 10$
$^{132}Xe^{22+}$	920	$3 \div 5$

Beam sharing among Tandem, Tandem+ALPI and PIAVE+ALPI



3600 h/yr of beam on target

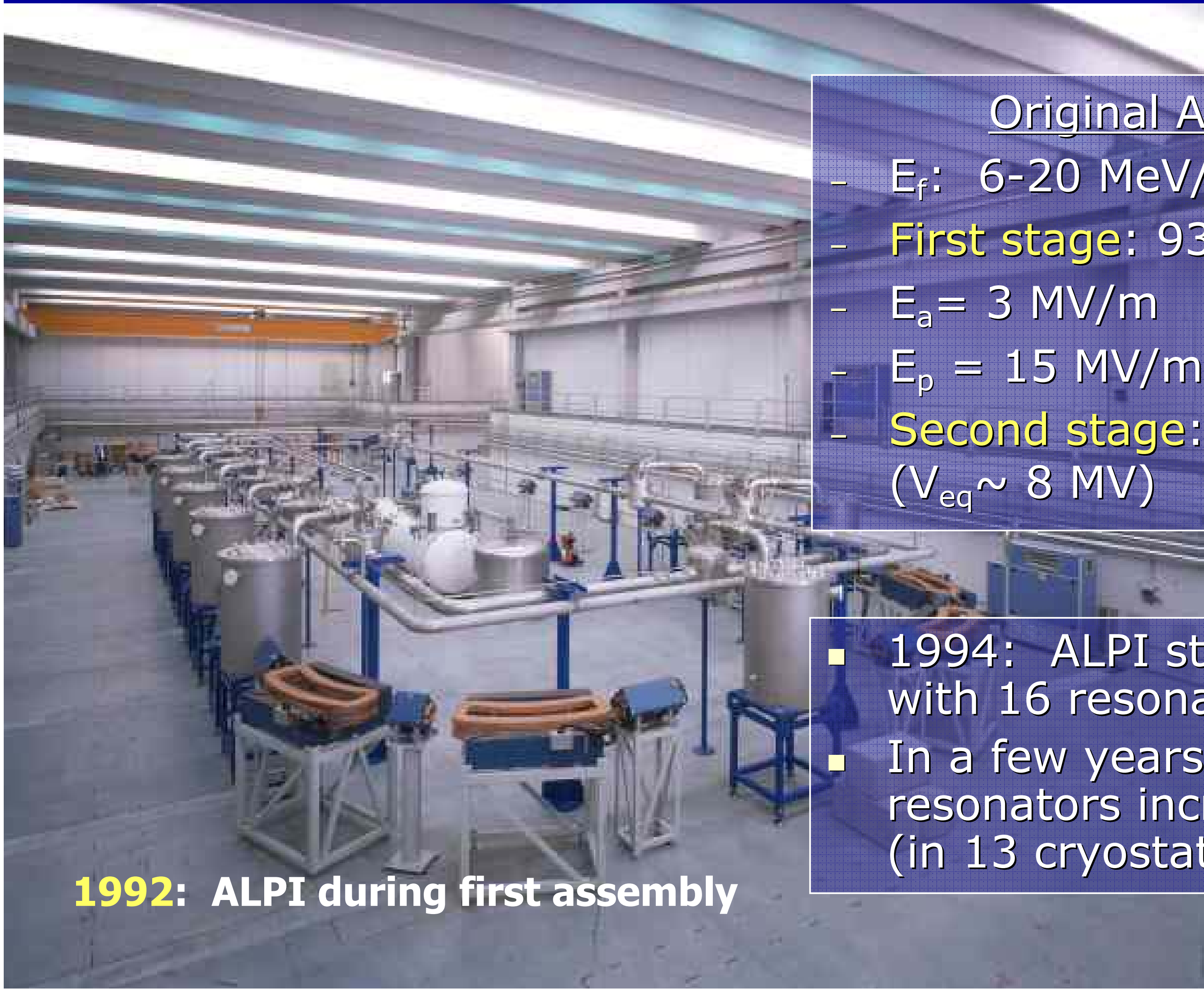


$^{136}Xe+^{208}Pb$
PIAVE+ALPI
E = 950 MeV
March 2007

Resonator performance and operation

1. Cu-based cavities
2. Full Nb cavities (QWRs and SRFQs)

ALPI superconducting linac ~ 70 Quarter Wave Resonators in 21 cryostats, @ 4.2 K



1992: ALPI during first assembly

Original ALPI Plan

- E_f: 6-20 MeV/u,
- First stage: 93 Pb/Cu QWR,
- E_a= 3 MV/m
- E_p = 15 MV/m
- Second stage: ECR+SRFQ (V_{eq}~ 8 MV)

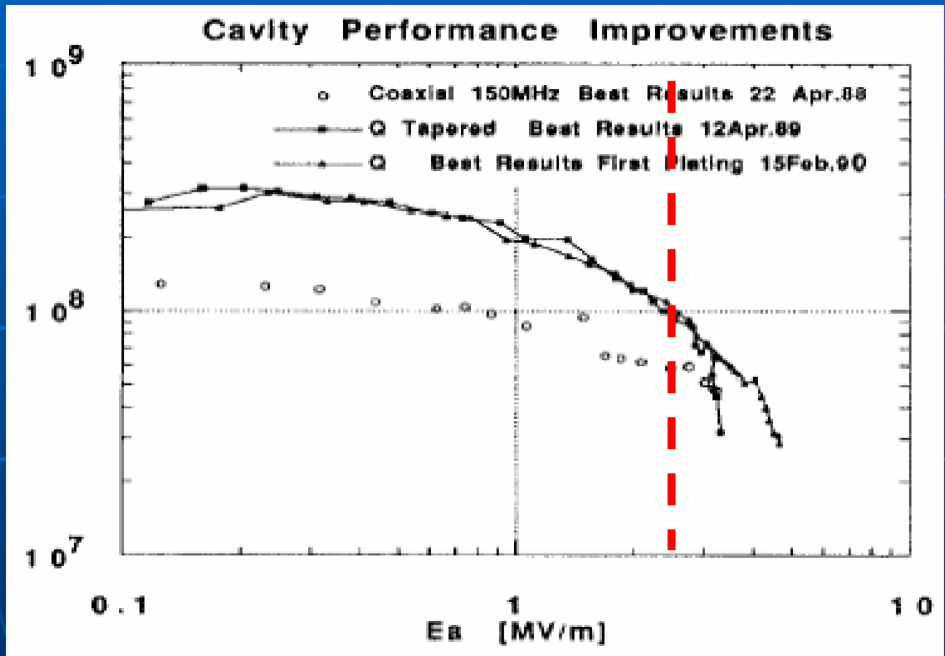
- 1994: ALPI starts operation with 16 resonators
- In a few years the number of resonators increased to 48 (in 13 cryostats)

Three technologies launched for QW Resonators

- **Pb/Cu : initial phase, readily available**
- **Full Nb R&D**
- **Nb/Cu (sputtering) R&D**

1990: Pb/Cu technology validated

$\beta_0 = 0,11$



E_a = 2.3÷2.7 MV/m

- Reliable operation
- Cheaper than full Nb, mechanically stable, not susceptible to quench, ideal for complicated geometries
- Limited performance, and some degradation of E_a

1994-1998: Completion of Pb/Cu ALPI section at $\beta_0 = 0,11$

Meanwhile: R&D on full Nb and sputtered Nb resonators launched

Nb/Cu, 160 MHz, β_{opt}~0,13

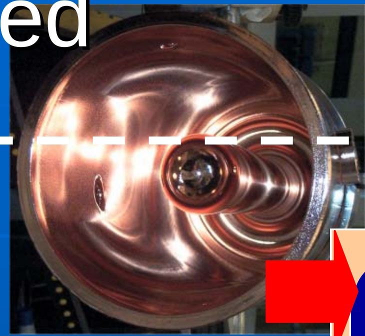
Full Nb, 80 MHz, β_{opt}~0,055

- **QWR by Nb/Cu DC biased sputtering** - Start in1988, first prototype in 1991 , a modified prototype (rounded shorting plate) reaches nearly top performance **in 1993**

  Q_0~1,5x10^9, E_a ~ **6 MV/m** at 7 W
- **Full Nb QWR** - prototypes for 80, 160, 240 MHz, first Q-curve of low β 80 MHz full Nb cavity **in 1993**

  Q_0~1,2x10^9, E_a ~ **6 MV/m** at 7 W

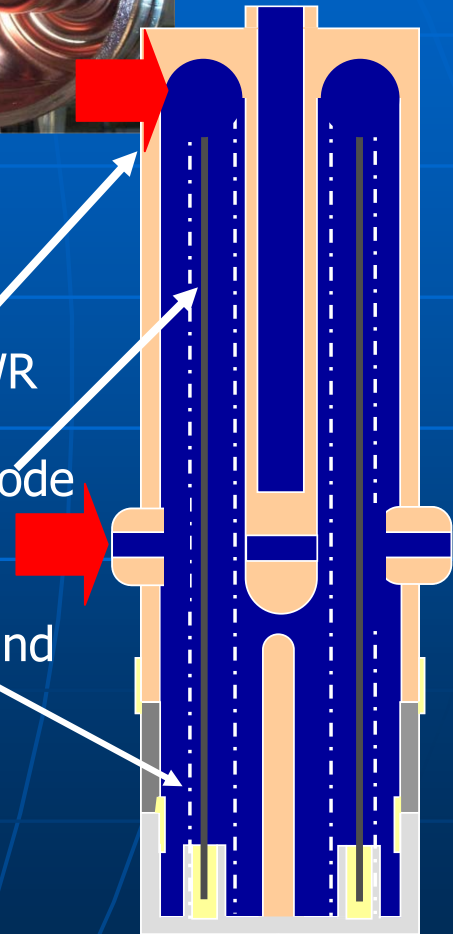
1996: first cryostat with higher β_0 Nb/Cu resonators installed



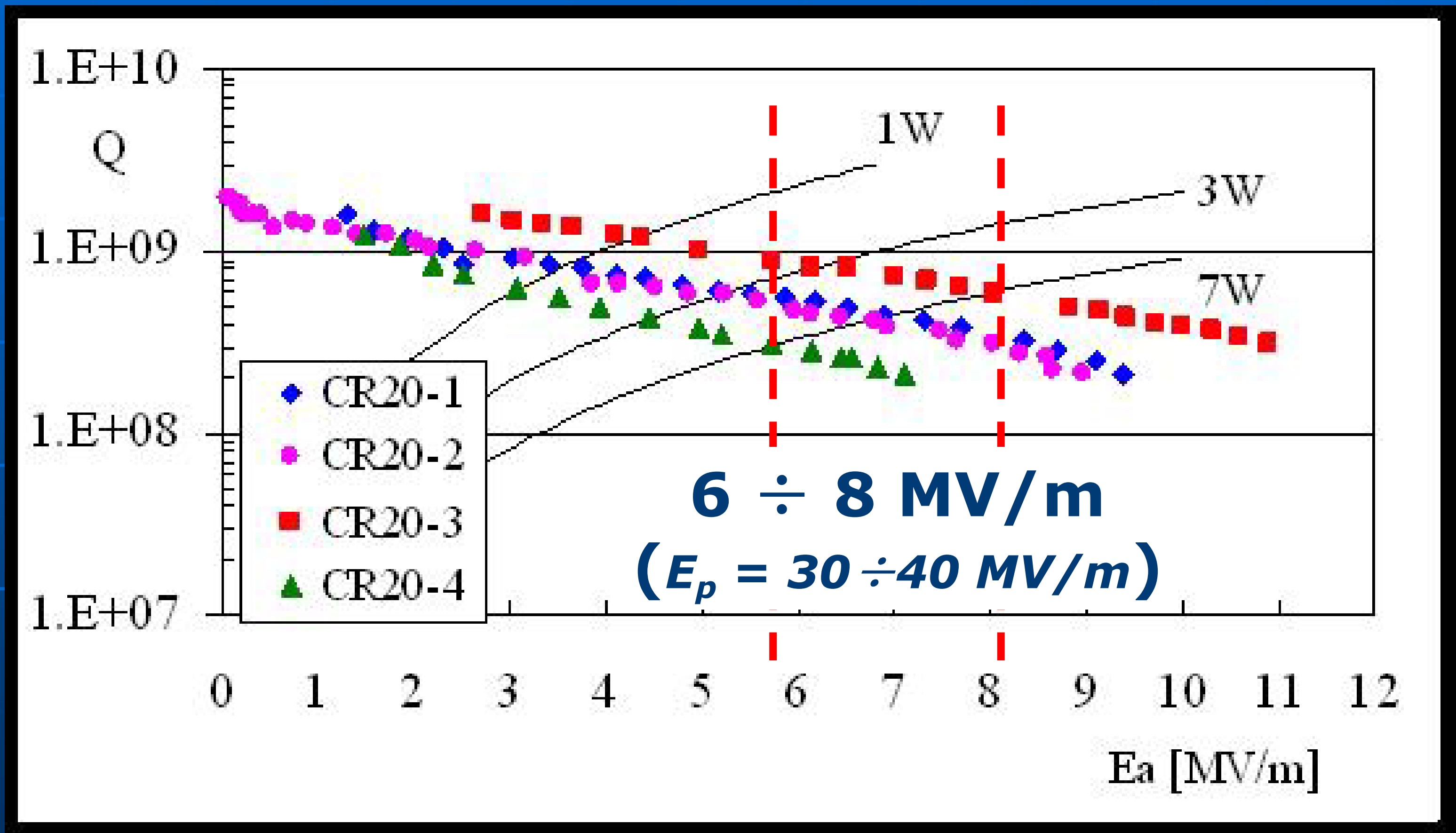
β_0 = 0,11

β_0 = 0,13

- Retracted beam ports (β_0 0,13)
- Rounded shorting plate
- Capacitive coupler (no hole in high j region)
- Material: 99,95% OFHC Cu, no brazed joints on cavity, collar nor supports
- $E_a \sim 6 \div 8$ MV/m ($Q_0 \sim 6 \div 7 \times 10^8$)

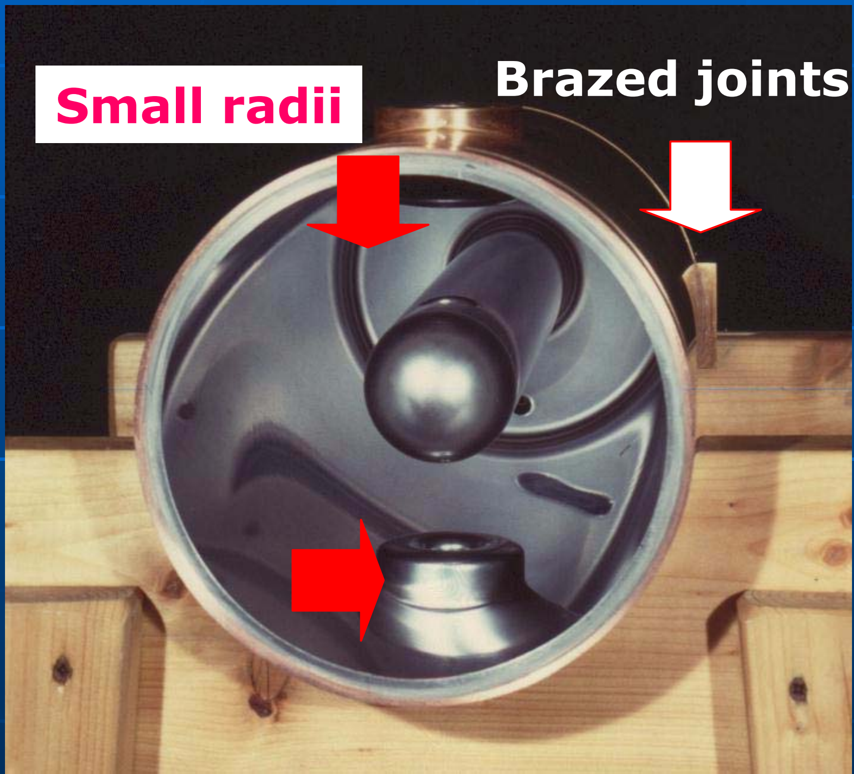


Off-line Q-curves of Nb/Cu sputtered resonators



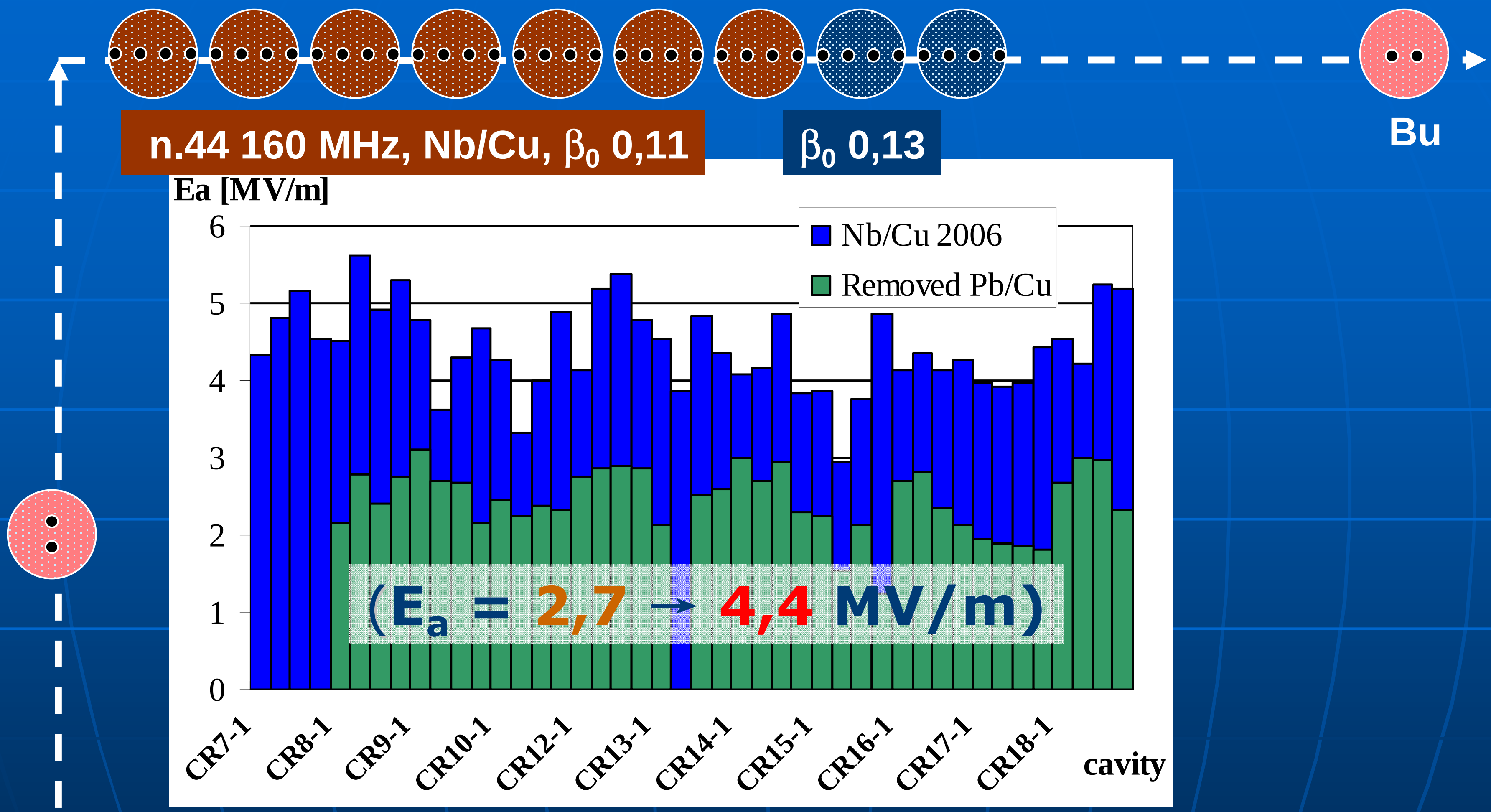
On line E_a: beyond 6 MV/m
Phase stability is not an issue ($\Delta f/\Delta P$ ~ 0,01 Hz/mbar)

From 1999: application of the sputtering technology on all β_0=0,11 cavities (Pb → Nb)

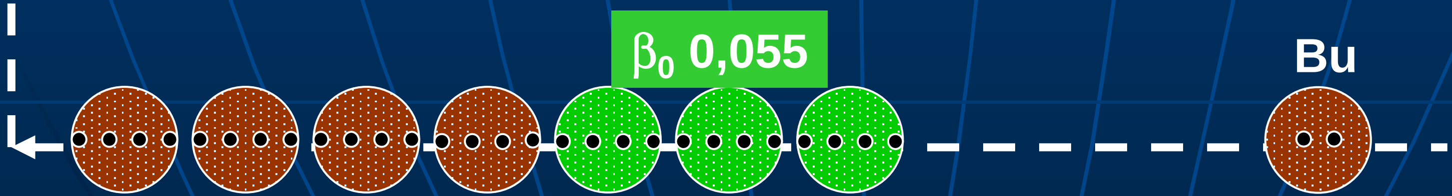


- From 1999 urgent major maintenance on all mid β cryostats: **4 leaking units** – cryogenic valve, actuated by a 16 bar He circuit
- Meanwhile: preparation of mid β Cu substrates for Pb replacement with Nb
- Despite: smaller shorting plate radii, sharp edges on beam ports and coupling holes, brazed joints (brazing junk released during sputtering)

2003: Mid β_0 section upgrade completed

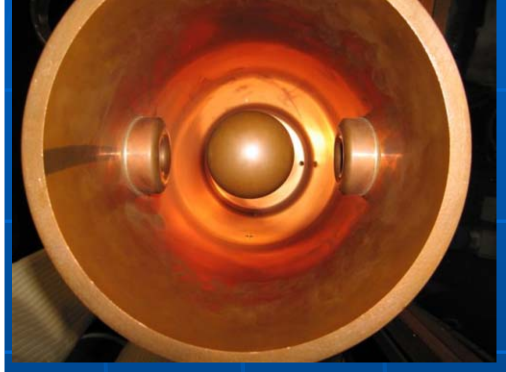


(carried out with **no interference with ALPI physics programme**)



On going R&D: Further improvement in mid β QWR performance

Old shape

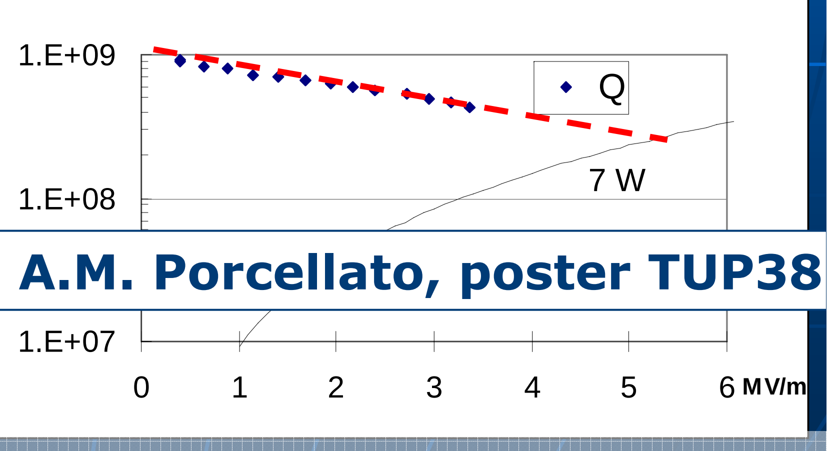


New shape

After sputtering

LNL is prototyping 4 new β_0 0,11 resonators:

- Beam ports by extrusion (rounded edges)
- Rounded shorting plate
- Capacitive coupler
- No holes in high current regions
- No brazing in outer resonator body



A.M. Porcellato, poster TUP38

Present lab RP authorization: 3 MV/m
Expected in ALPI: ~ 4,4 → **5,5 MV/m**

Resonator performance and operation

1. Cu-based cavities
2. Full Nb cavities (QWRs and SRFQs)

Full Nb QWR section (80 MHz, β=0,55)

β_0 0,11

β_0 0,13

Bu

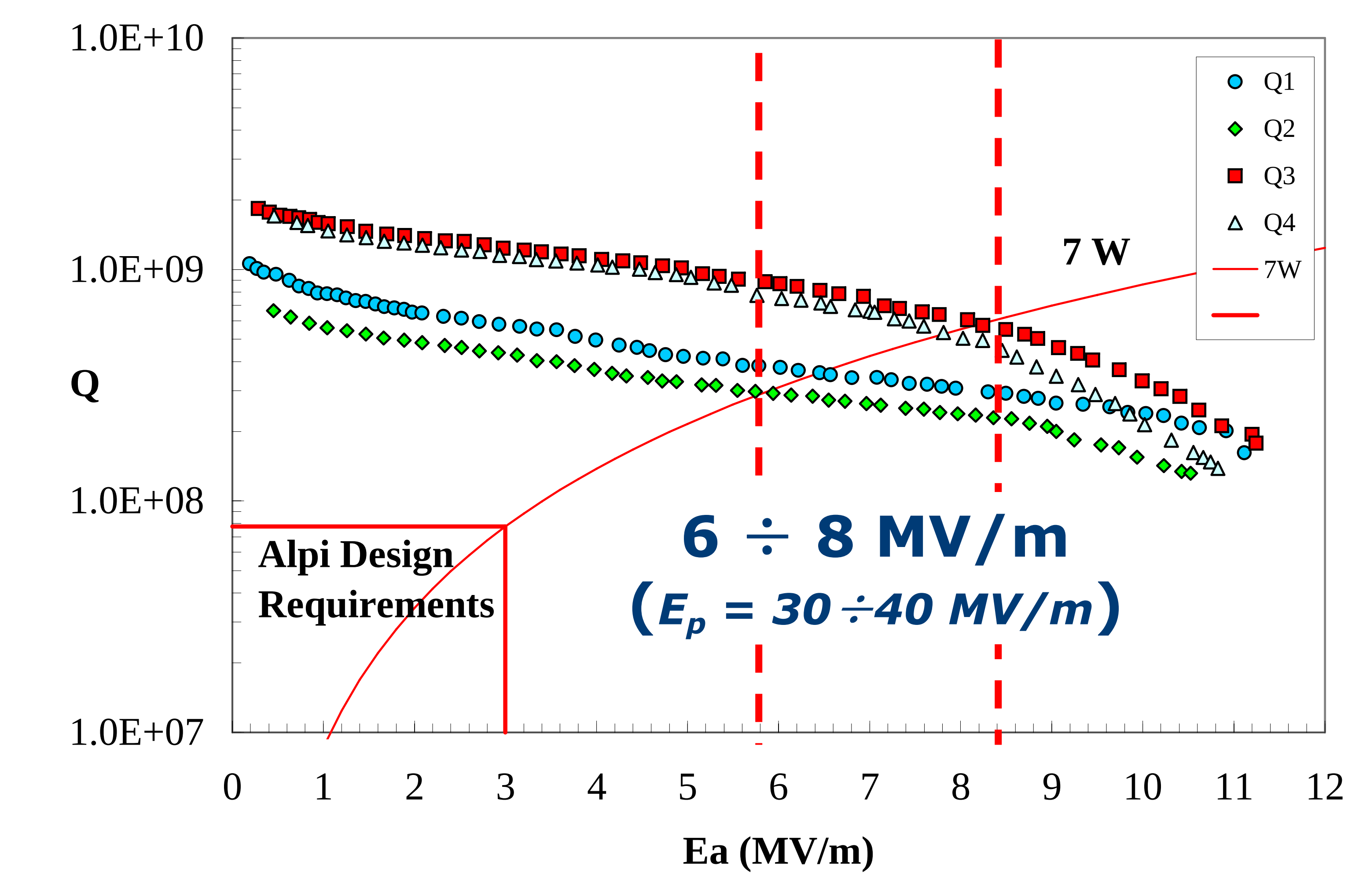
Outer conductor: double wall instead of explosive bonding (high T treatments possible)

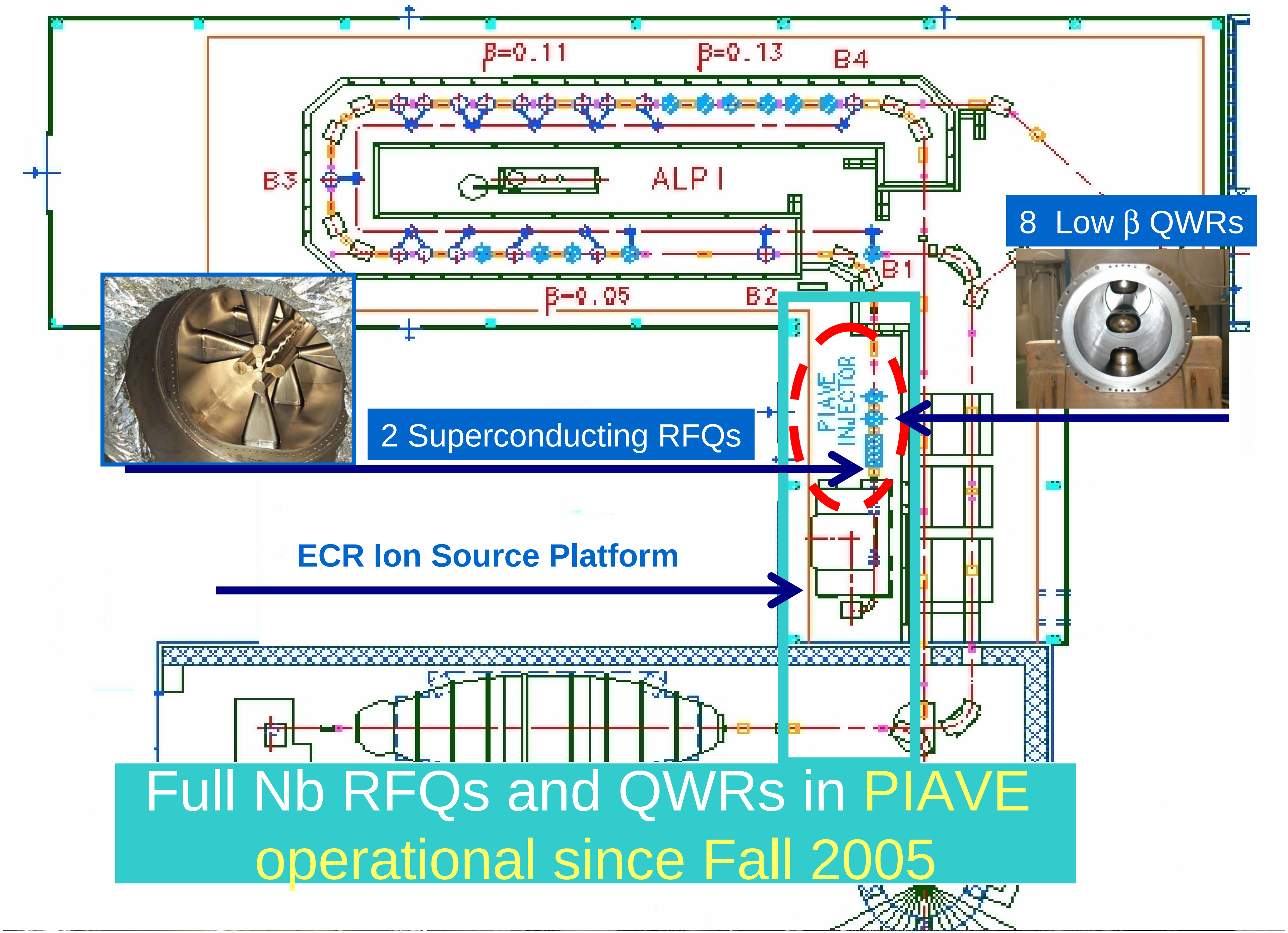
- Prototypes (at 80, 160, 240 MHz) till 1993, then production of n.12 80 MHz β_0=0,055 cavities
- Indispensable for A>100 Tandem beams and all PIAVE beams
- In 1998: 12 resonators were installed in ALPI

n.12 80 MHz, full Nb, β_0 0,055

Bu

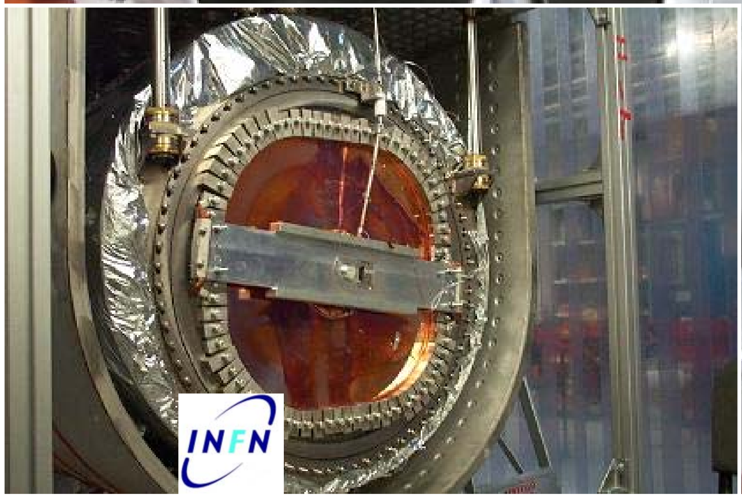
Off-line Q-curves of full Nb QWRs





Full Nb RFQs and QWRs in PIAVE operational since Fall 2005

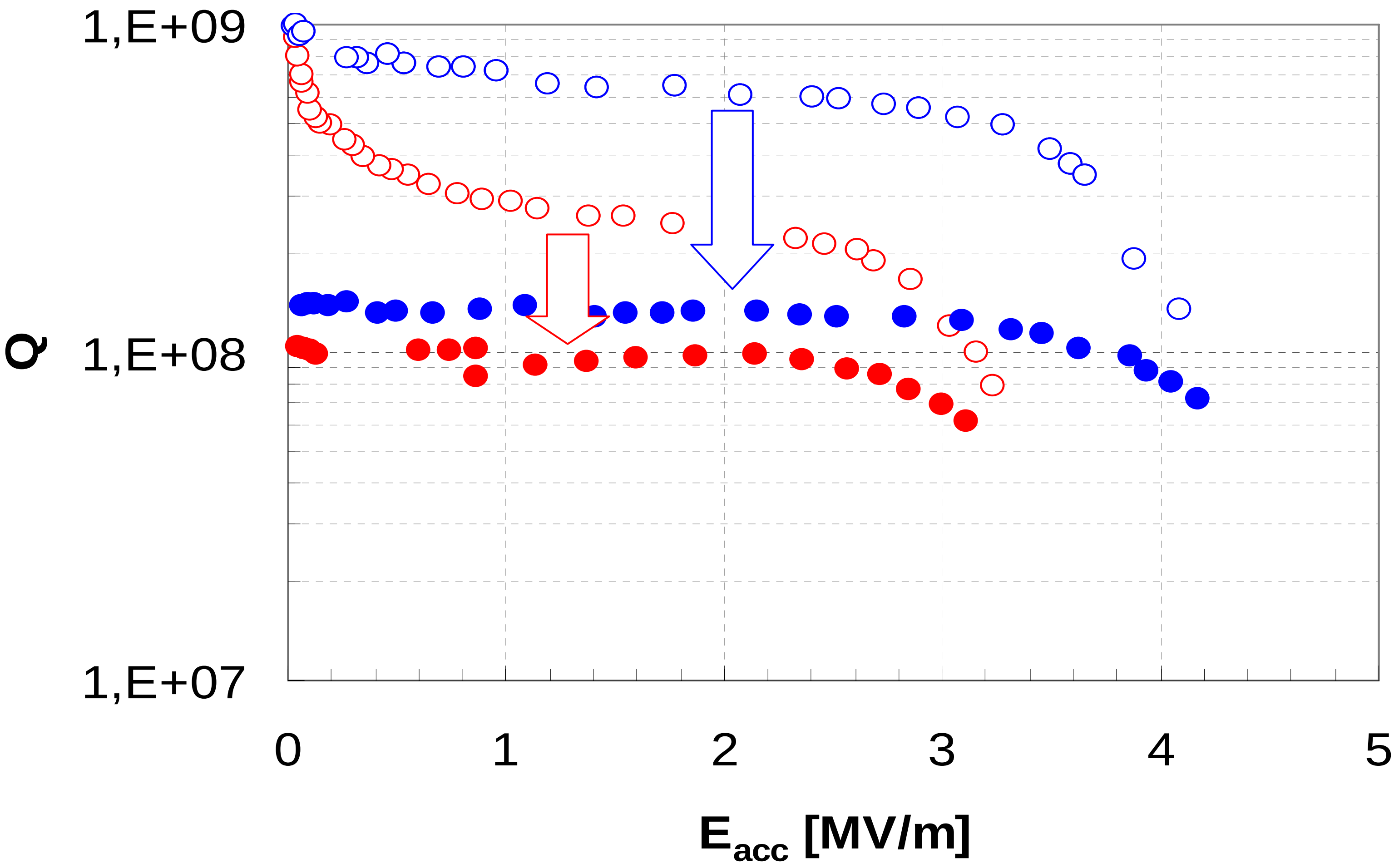
Superconducting RFQs



ACHIEVED RESULTS

1. Q vs E_a curve as specified
2. Frequency locking by means of VCX (vibrations) and mechanical tuners (liquid He preassure breathing), after ensuring gentle cryogenics conditions
3. Classical RFQ split into 2, with external bunching (relative phase must be found)
4. ± 0,2 mm alignment on beam axis for good transmission

SRFQs Q-curves



Q-curves loaded by the VCX fast tuners

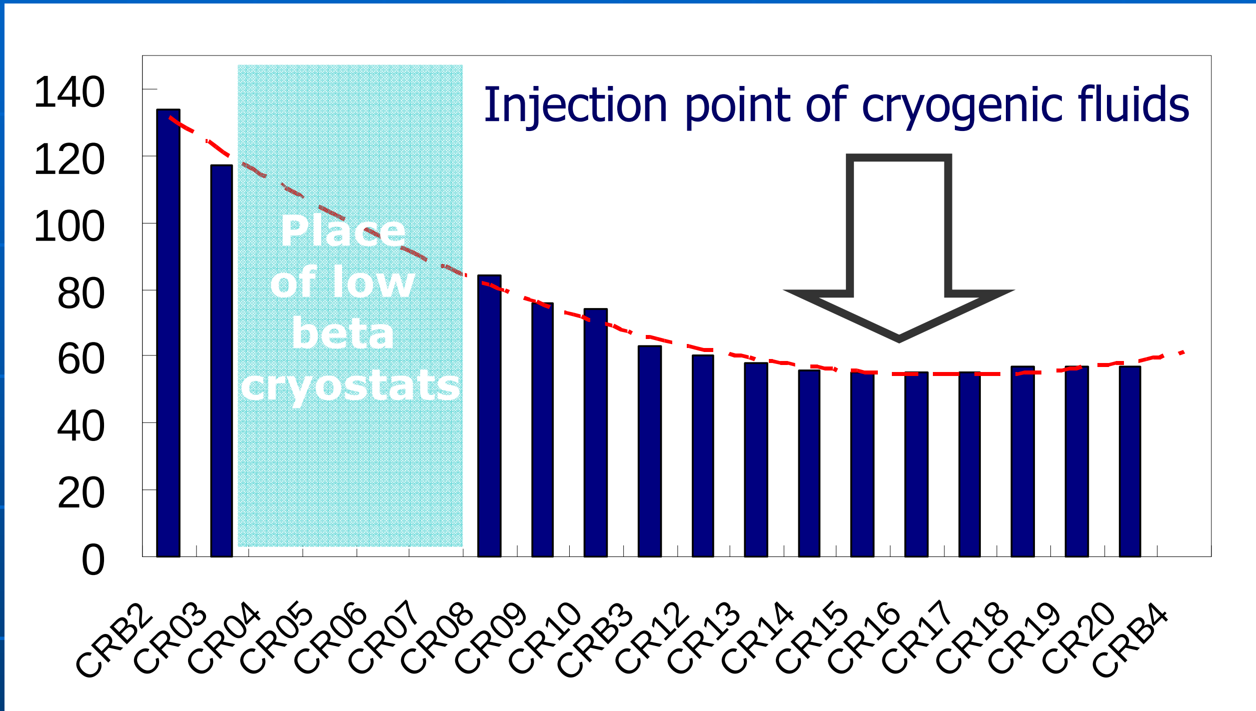
Difficulties and challanges in full Nb resonators

- A zero order problem for QWRs: the cryogenic system cannot feed lower β_0 full Nb QWRs reliably (1998, solved 2004)

- Phase stability vs slow P changes and mechanical vibrations

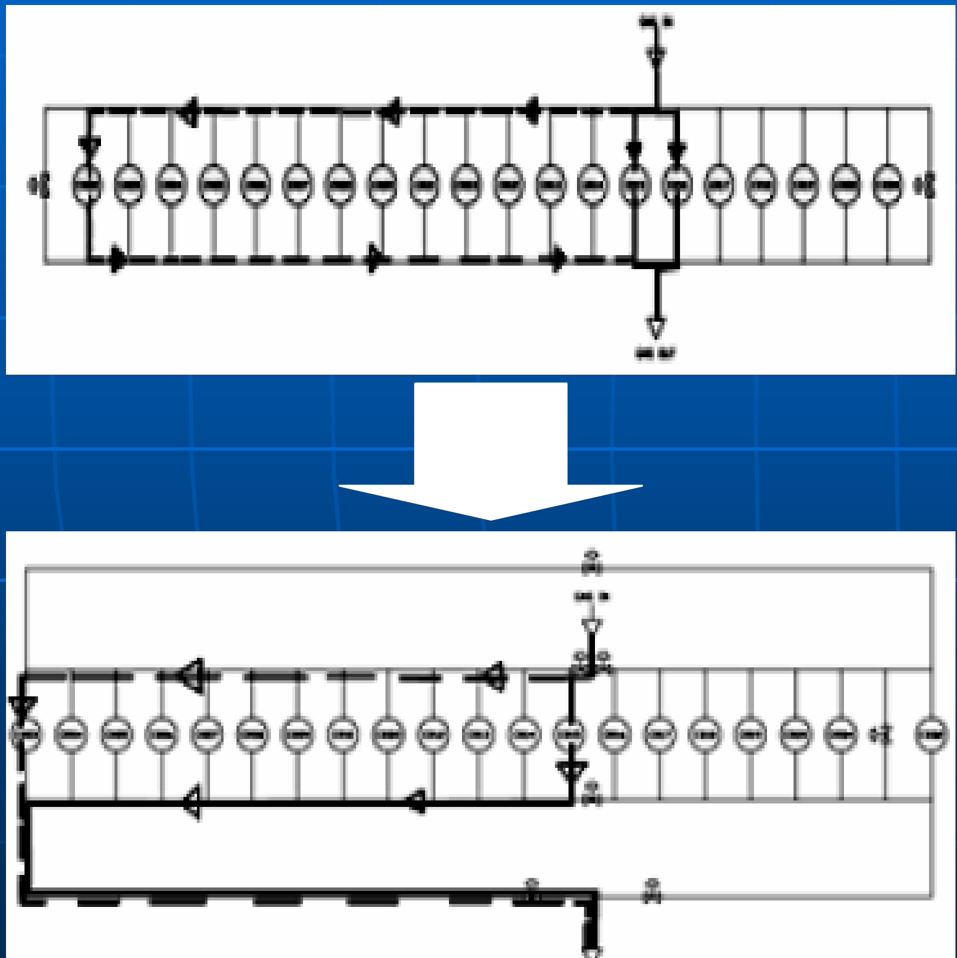
- QWRs: improved slow tuners, dampers ($E_a \sim 3 \div 4$ MV/m), new RF system (aim: *5 MV/m*)
- SRFQs: 2 large range tuners each, VCX Fast Tuners (ANL design)

Problem in feeding low β resonators with gas and liquid He



- 1996-1998: observation of **unbalanced cryogenic loads** Shield T (He gas) increases towards low β linac far end
- **Ineffective shield cooling → anomalous liquid He evaporation → No liquid He transfer** (CR04÷CR06 could not accumulate liquid He!)

2004 - Upgrade of ALPI cryogenic lines



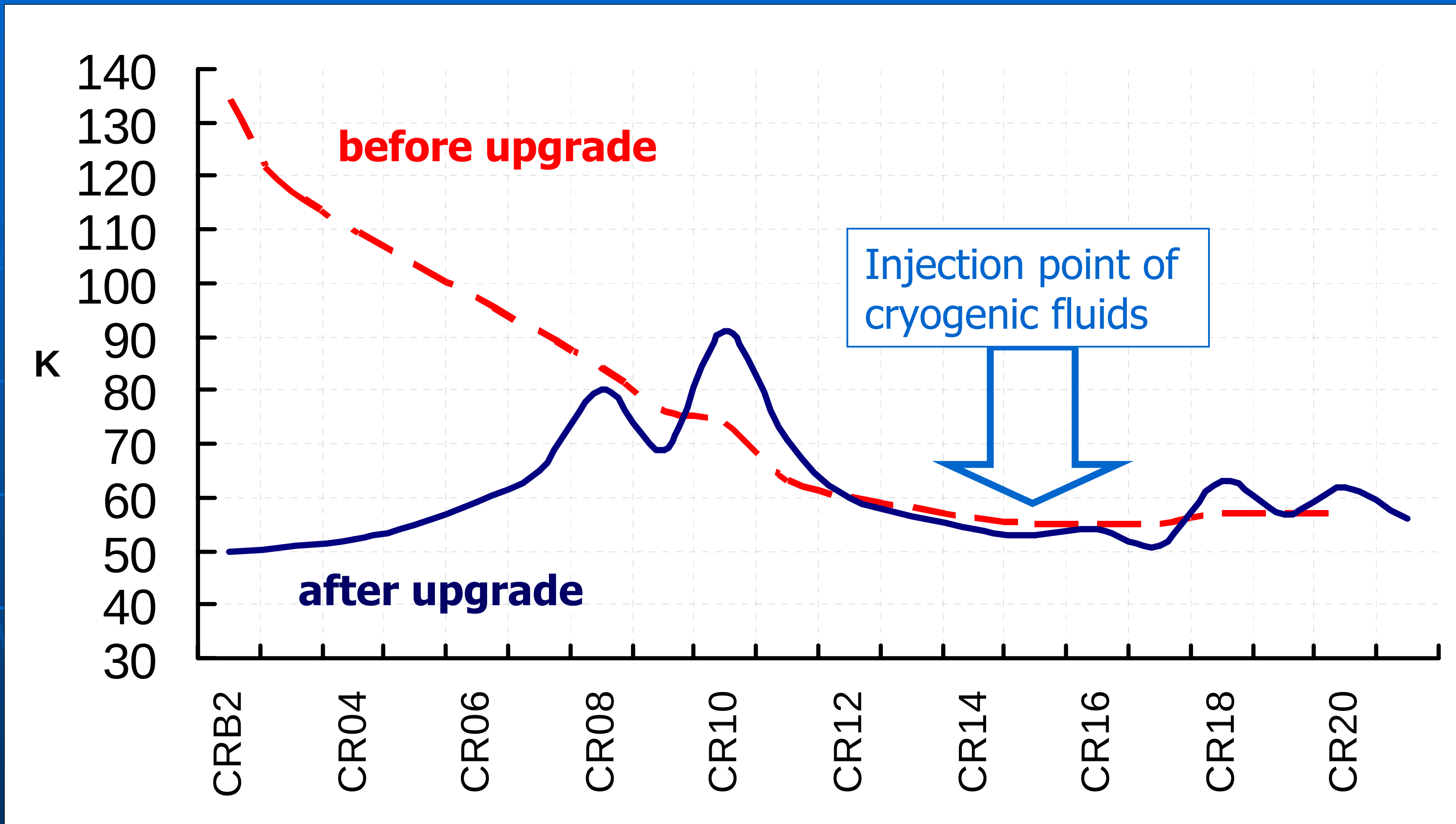
- 2004: scheduled ALPI stop

  Cryogenic lines system reshaped

- ΔP = constant on each cryostat

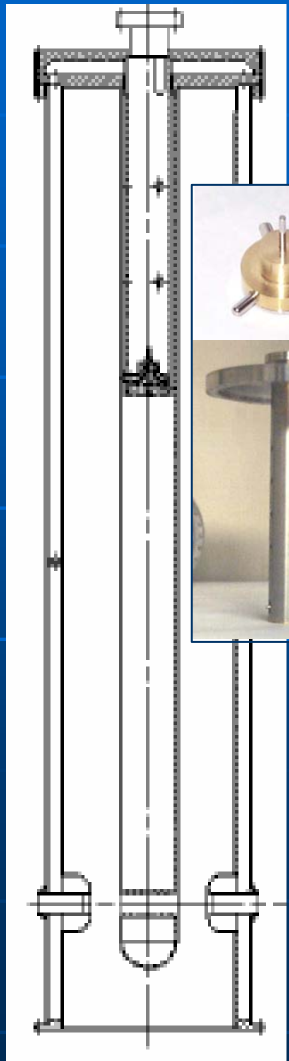
- Additional tools mounted:
  - 4 valve boxes
  - P and T sensors
  - 2 mass flow meters

Result of the upgrade

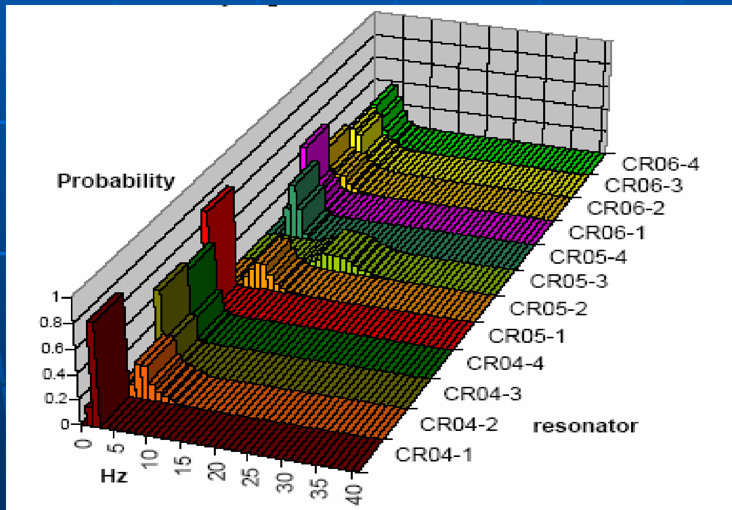


Shield temperatures are now much better balanced (whole linac cooling possible)

Noisy cryogenics urged the development of mech. Dampers for QWRs

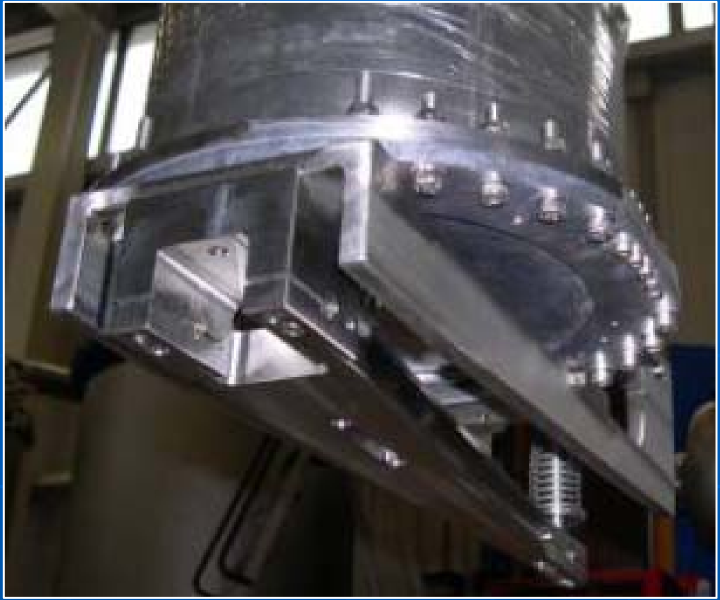


- **Liquid He P** occasionally changes by **100 mbar/min**
- **(Cu-based cavities: 0,01 Hz/mbar)**
- **Low beta QWR**: **Δf/ΔP** up to **1 Hz/mbar**
- **Mechanical dampers** can compensate up to **10 Hz/min** changes (Modes at 42 Hz and 22 Hz)



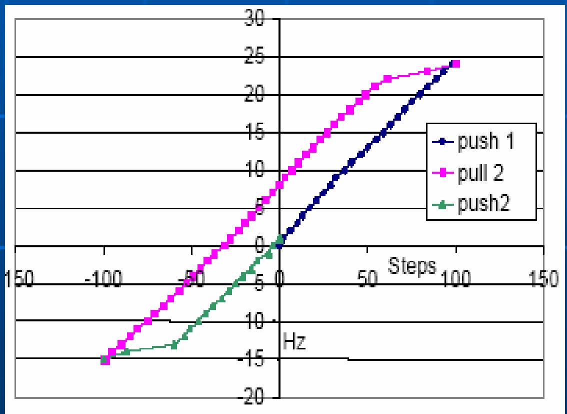
Recording of amplitude distribution of frequency oscillations

- **Large He P jumps** must be either **eliminated** or compensated by **damper + efficient slow tuner**



Slow tuners upgrade

- Replacement of standard cam-shaft tuner with the TRIUMF design QWR tuner actuated by a standard stepper motor
- Very small and reproducible **backlash**
- **Resolution better than 0,33 μm** (equivalent to **1 Hz frequency steps**)
- Little magnetic material and no lubricants

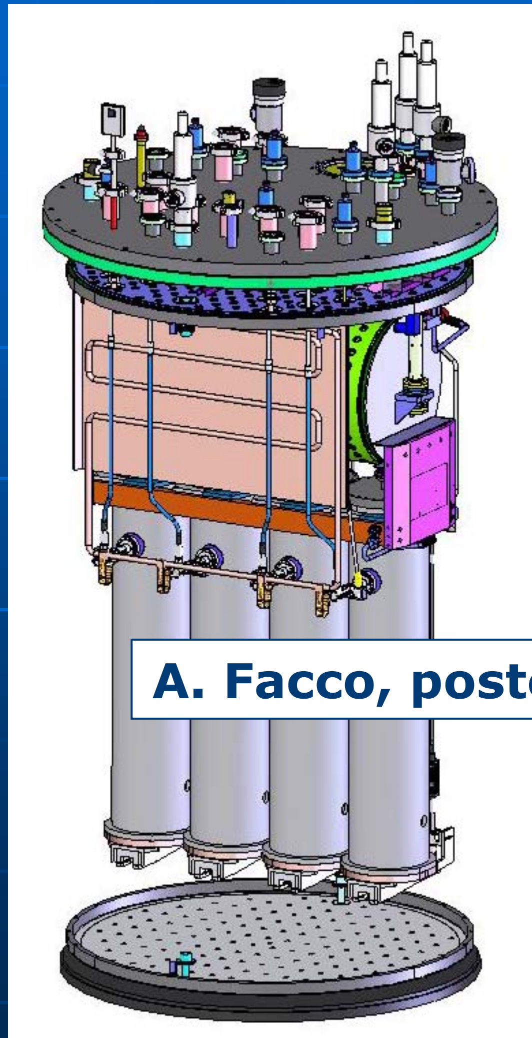


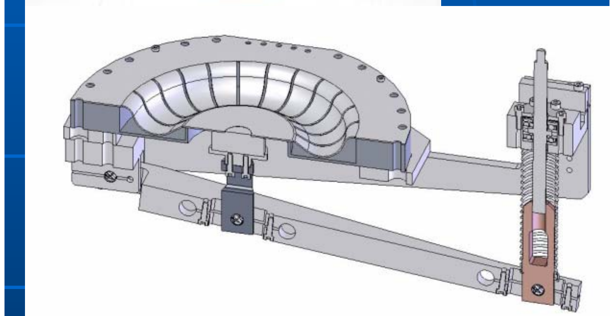
Result: thanks to work on **cryogenic lines**, **mechanical damper**, **slow tuner** full Nb QWR **operate at nominal field (3 MV/m)**, still limited by **RF system**

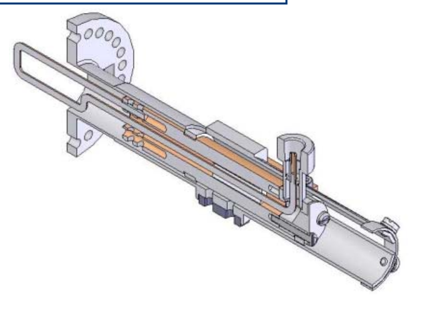
Present low β_0 QWR upgrade: RF system

- One more low β_0 cryostat with 4 cavities
- P_{ampl} = 150 → 1000 W
- Upgraded rf system
  -LN cooled couplers
  -LN cooled RFlines
- More efficient "slotted" slow tuner

Expected result:
E_a = 3 → 5 MV/m



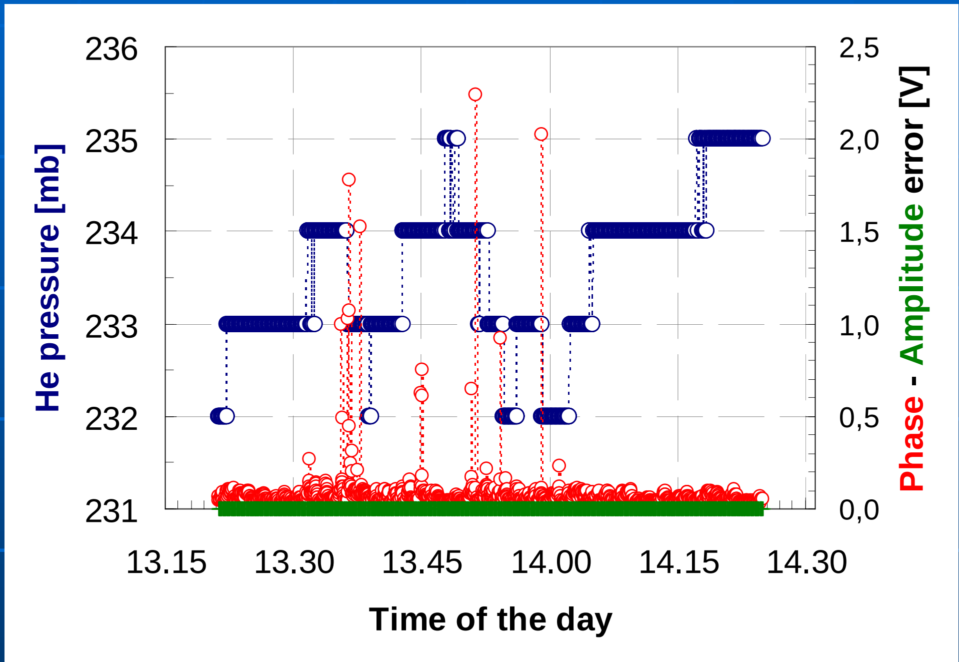




A. Facco, poster WEP08

SRFQs phase locking issue

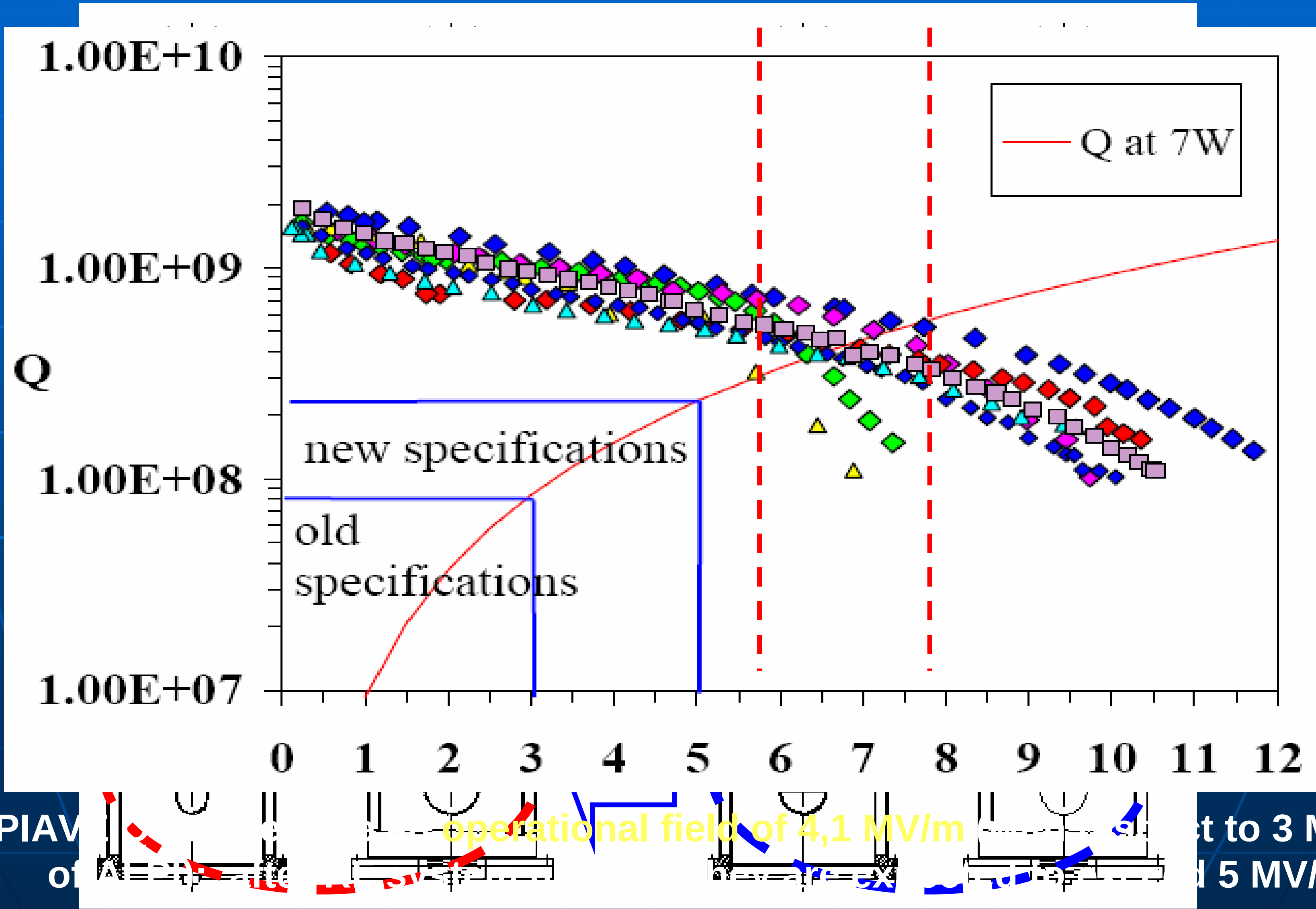
$\Delta f/\Delta P \sim 40$ Hz/mbar !



- Gentle cryogenics
- VCX Fast Tuner (ANL design)

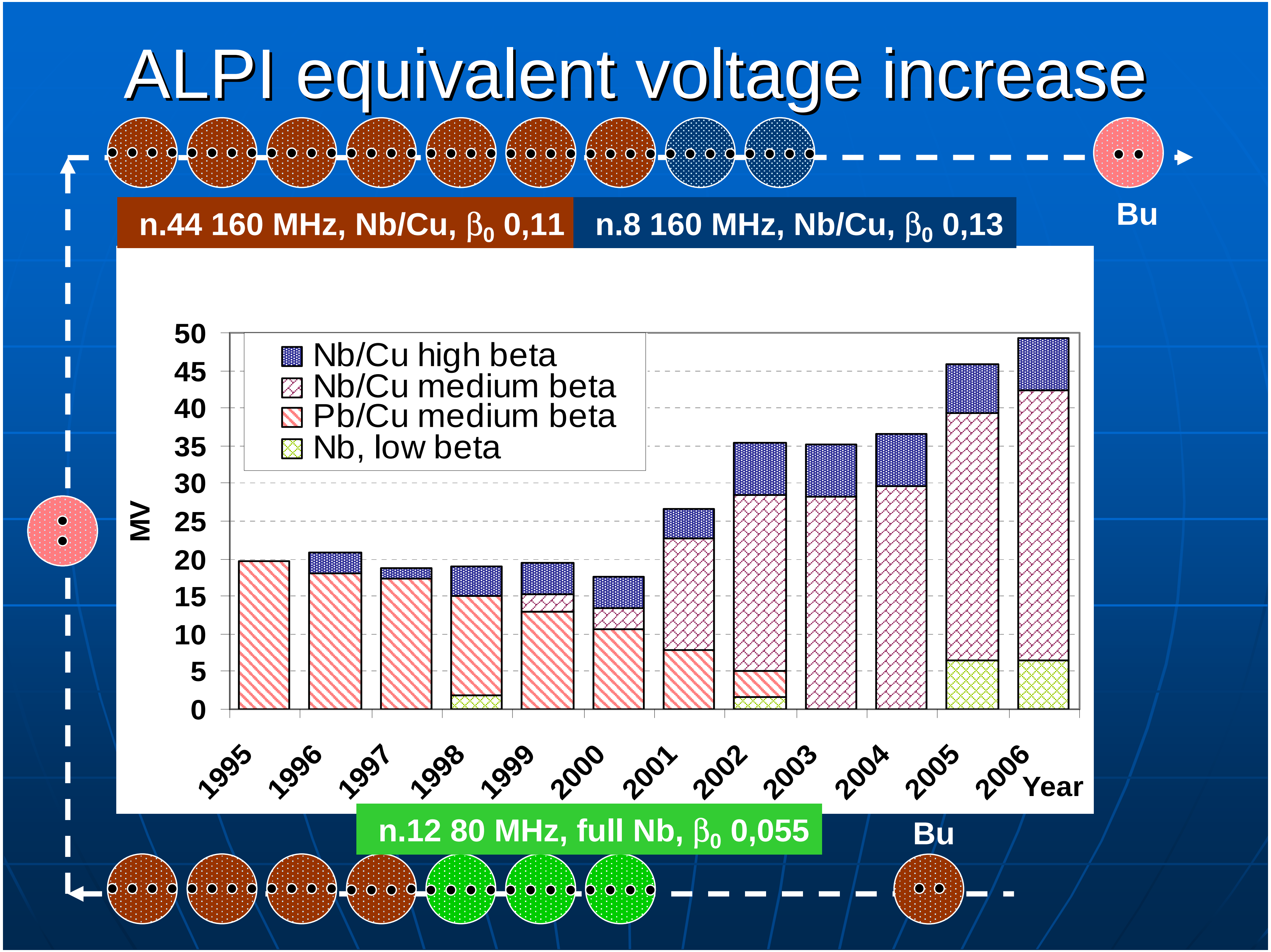
- They work very nicely as long as **liquid He $\Delta P/\Delta t$ < 5 mbar/min** (usually the case)
- Only drawback: early inexperience in using their electronics properly caused an avalanche of PDS shorts → extraordinary cryostat maintenance in Spring 2006

SRFQs are followed by 8 full Nb QWRs



PIAV … operational field of 4,1 MV/m … t to 3 MV/m

of … 5 MV/m



ALPI equivalent voltage increase
n.44 160 MHz, Nb/Cu, β0 0,11
n.8 160 MHz, Nb/Cu, β0 0,13
Bu
Nb/Cu high beta
Nb/Cu medium beta
Pb/Cu medium beta
Nb, low beta
MV
0
5
10
15
20
25
30
35
40
45
50
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
Year
n.12 80 MHz, full Nb, β0 0,055
Bu

Operational comparison of QWR (Nb/Cu and Full Nb) and SRFQs

	Nb/Cu QWR	Upgraded Nb/Cu	Full Nb QWR	Full Nb SRFQ
$\bar{E}_a$ [MV/m]	6,5	4,5	6,5	2,2 / 3,2
$\bar{E}_p$ [MV/m]	32	22,5	32	25
$\bar{E}_{a,op}$ [MV/m]	6	4,4	3 / 4,1	1,9 / 2,8
RT RFE conditioning [h]	48	48	96	32
Cooldown time per cryostat [h	8÷12	8÷12	18	12
4K RFE conditioning [h]	None	None	2	20
HPPP [h]	4	4	None	100
He conditioning [h]	6	6	6	20
Q-disease	None	None	Some	None
Deconditioning	None	None	None	On SRFQ2
Phase locking tools	O.C.	O.C.	O.C.+Damper	VCX
Unlock rate [day^{-1}]	0	0	0÷5	0÷5

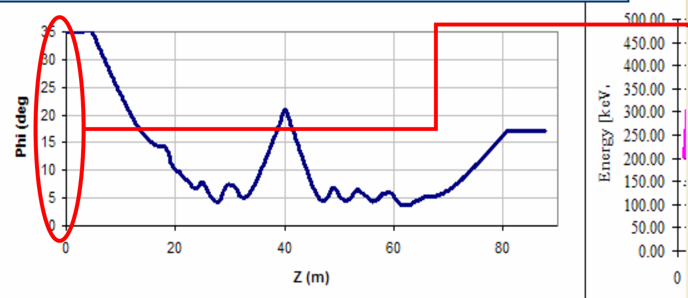
Setup of E_a and ϕ of resonators

First step: Longitudinal dynamics is defined in a dedicated spreadsheet

Microsoft Excel - Zn_70.xls

Example: a Tandem-ALPI $^{70}Zn^{10+}$ beam (E_{fin} = 450 MeV)

Heb L_{eff} (m)	0.18
QWR L_{eff} (m)	0.18
Tandem	
m_0 (MeV)	931.50
q	10
m	70
E_{kin} (MeV)	140.7
beta	0.0655872
E_{kin}	2010.00
e (Coul)	1.60E-19
c (m/s)	3.00E+08
Brho (T m)	1.427



70 10 (m and q) 456.7 MeV 6.52 MeV/u — 09/06/2007 7.10

cry. #	cav. #	Nom. beta	Eacc MV/m	VT MV	on off	TTF	Phis deg	E gain keV/u	Energy keV/u	beta	Brho T-m	Energy MeV	B (Tesla)
CRB2	1	0.11	0.44	0.038	1	0.49	-90	0.00	2010.0	0.0656	1.430	140.70	0.7524
CR04	1	0.056	3.00	0.526	1	0.97	-20	70.59	2080.6	0.0667	1.455	145.64	0.7655
	2	0.056	1.00	0.000	0	0.97	-20	0.00	2080.6	0.0667	1.455	145.64	0.7655
	3	0.056	3.50	0.610	1	0.97	-20	81.89	2162.5	0.0680	1.483	151.37	0.7805
	4	0.056	3.00	0.519	1	0.96	20	69.72	2232.2	0.0691	1.507	156.25	0.7930
CR05	1	0.056	2.00	0.344	1	0.96	20	46.20	2278.4	0.0698	1.522	159.49	0.8011
	2	0.056	3.00	0.514	1	0.95	-20	69.02	2347.4	0.0709	1.545	164.32	0.8132
	3	0.056	3.00	0.511	1	0.95	-20	68.59	2416.0	0.0719	1.568	169.12	0.8250
	4	0.056	2.50	0.000	0	0.94	-20	0.00	2416.0	0.0719	1.568	169.12	0.8250
CR06	1	0.056	3.00	0.508	1	0.94	-20	68.17	2484.2	0.0729	1.589	173.89	0.8366
	2	0.056	3.00	0.505	1	0.93	-20	67.74	2551.9	0.0739	1.611	178.63	0.8479
	3	0.056	3.00	0.501	1	0.93	-20	67.32	2619.2	0.0748	1.632	183.35	0.8590
	4	0.056	3.00	0.498	1	0.92	20	66.90	2686.1	0.0758	1.653	188.03	0.8700

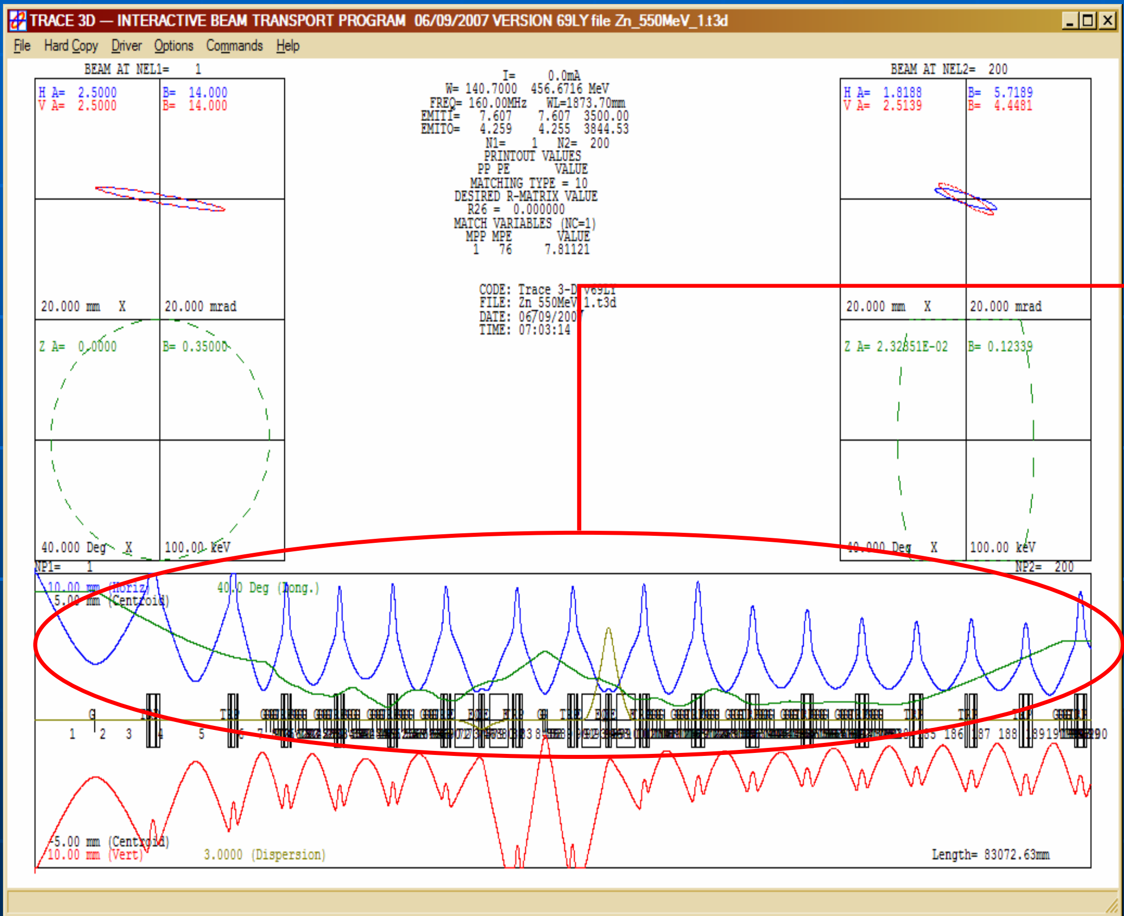
Riepilogo / ALPI con RFQ

The source buncher delivers **1.2 ns bunches** at **ALPI entrance** (i.e. 70deg@160MHz)

(tandem energy spread < 0.1 %)

Resonator +20° or -20° phases (and their amplitudes, in some cases) are regulated, so as to **minimize the average phase width** of the bunch and to keep its oscillations under control

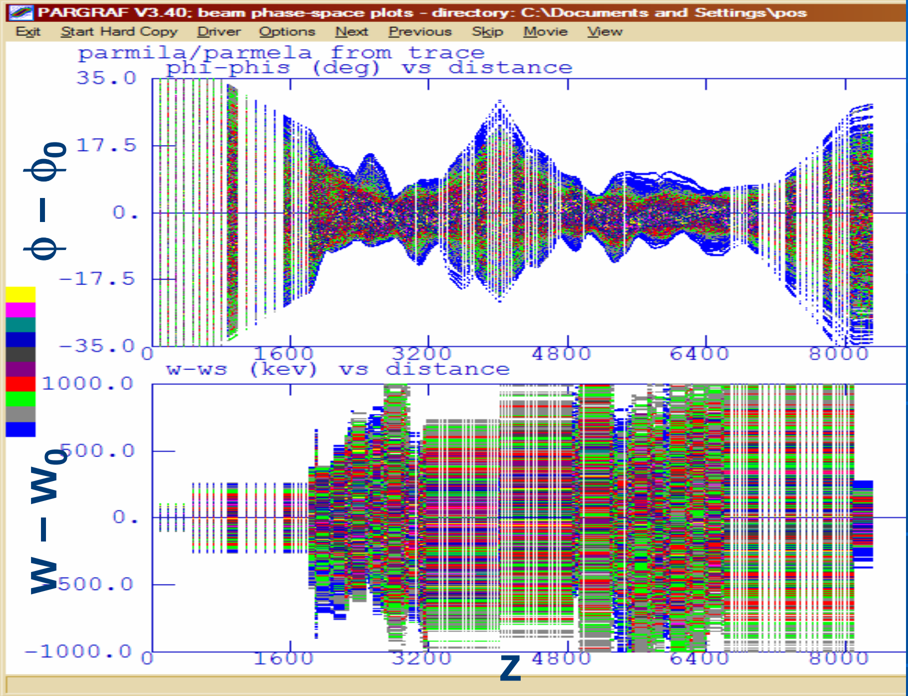
Second step: Trace3D calculates transevrse dynamics

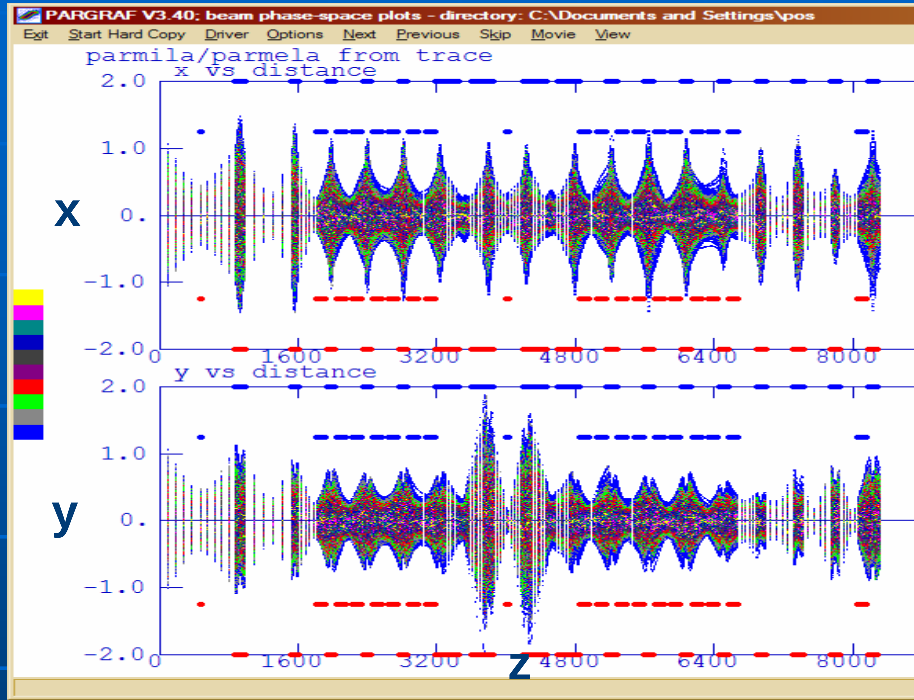


Longitudinal dynamics is inserted into a Trace3D sheet: **quadrupole gradients are regulated**, so as to have a beam which be **well enough focused in the cavities and not too large in the magnets**

Make sure that the chosen dynamics does **not** imply **too large quadrupole gradients**: otherwise back to Excel spreadsheet to changes resonators ϕ.

Third step: ALPI is simulated with PARMELA





1. Possible longitudinal beam losses (and their cause) are searched
2. Quadrupole gradients are corrected in order to minimize transverse losses

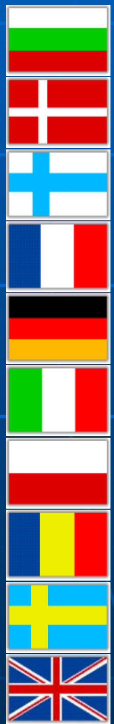
Future perspectives

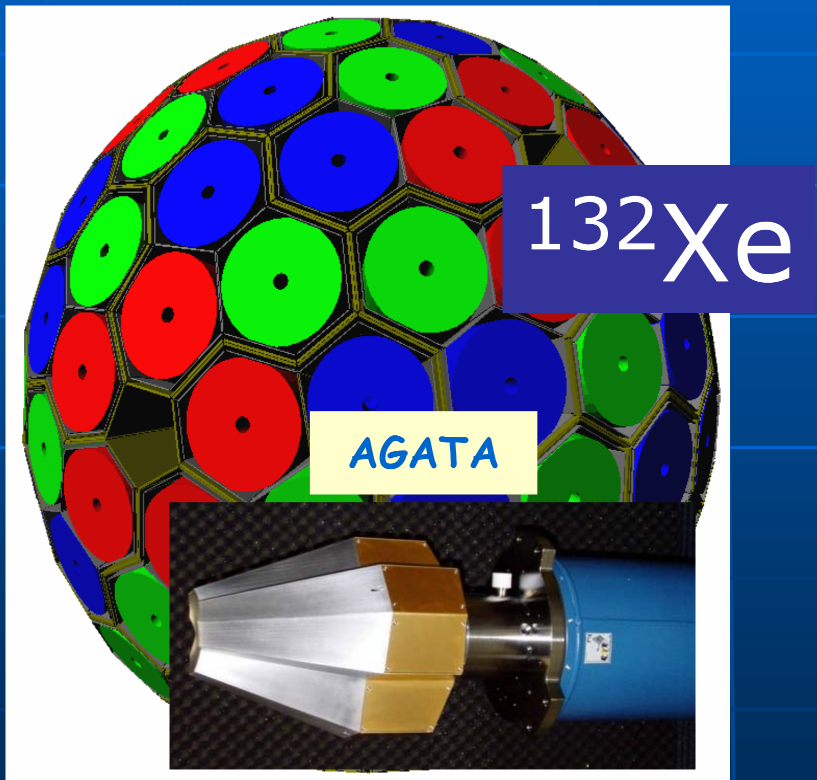
Challenges on SC cavity development from:

1. Experimental campaign with EU-detector AGATA
2. Use of PIAVE-ALPI as RNB accelerator

AGATA detector: a milestone for PIAVE-ALPI

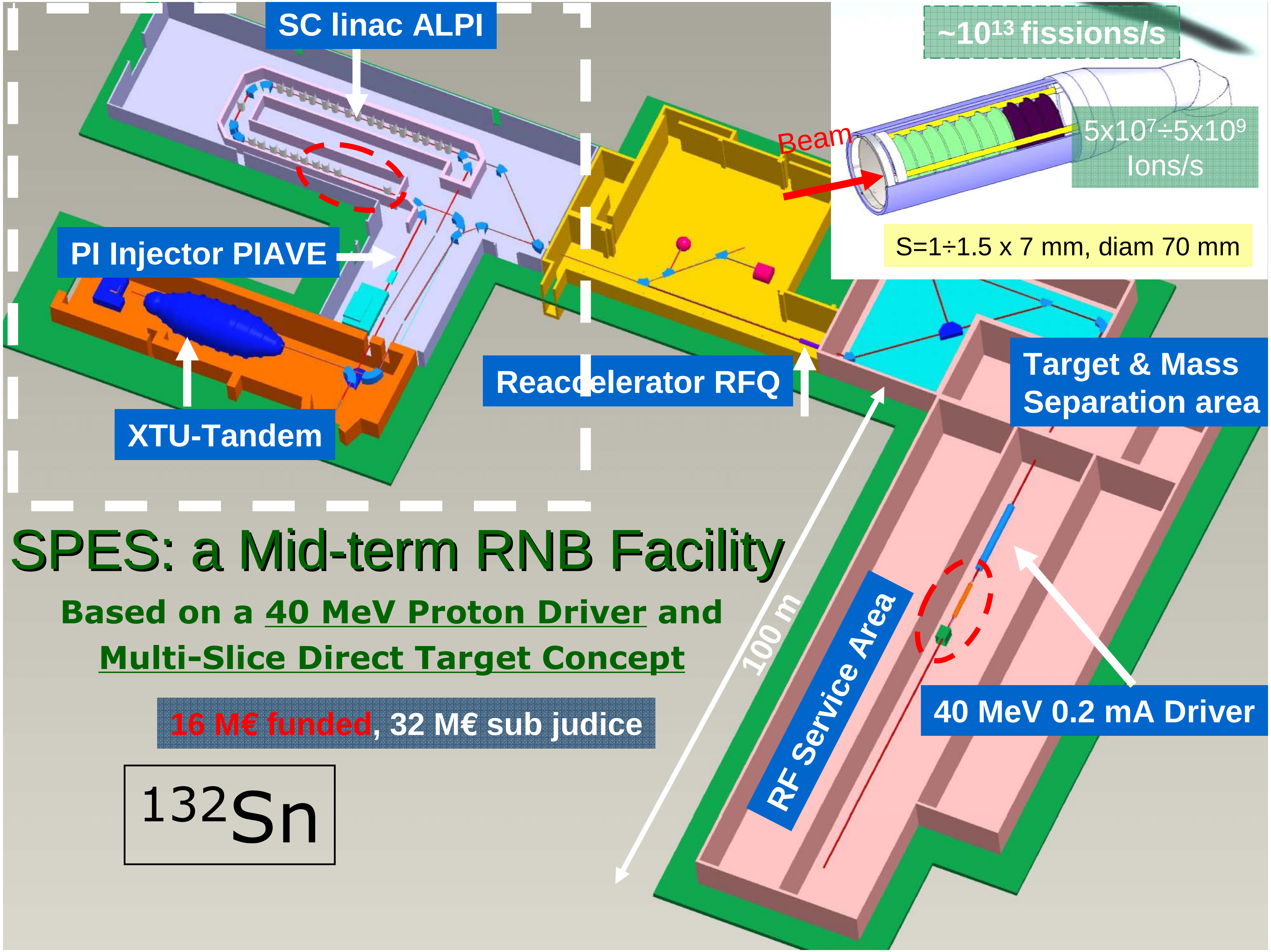
(**A**dvanced **GA**mma **T**racking **A**rray)
180 large Ge crystals, segmented 36 fold





- **4**π set of γ detectors, designed to be operational at European Laborarories offering high intensity stable and unstable beams
- Its demonstrator will be commissioned and tested for the first time **at LNL (I)** with PIAVE-ALPI beams (10/2008-04/2010)
- **GANIL (F)** (upgraded version): 2010-2012
- **GSI (D):** after 2012

To fulfill AGATA experimental specs: **higher currents and energies** of heavy ion beams are required on PIAVE-ALPI



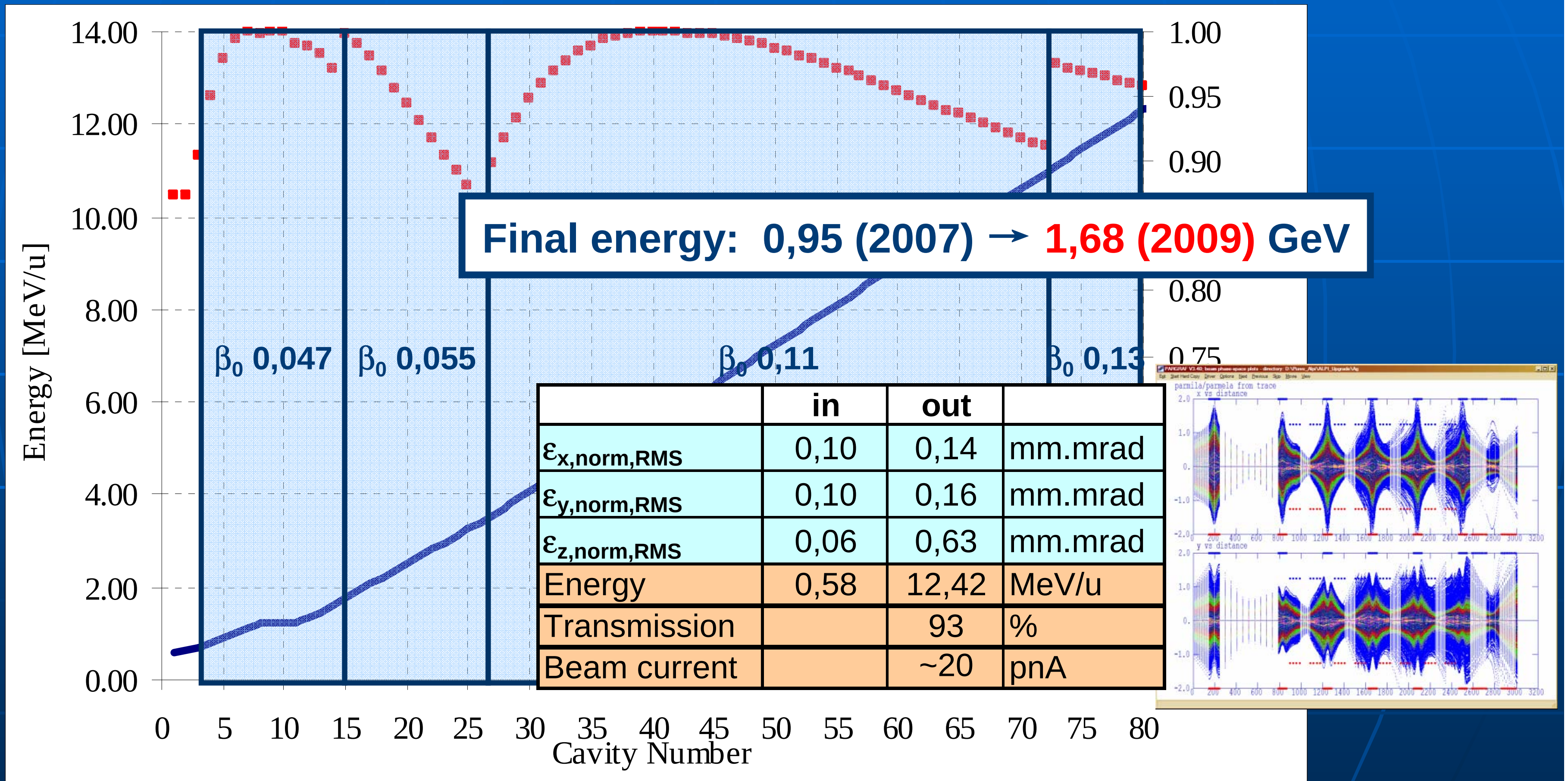
SPES: a Mid-term RNB Facility

Based on a <u>40 MeV Proton Driver</u> and
<u>Multi-Slice Direct Target Concept</u>

16 M€ funded, 32 M€ sub judice

^{132}Sn

$^{132}Xe^{36+}$ in 2009, with new ECRIS and upgraded low β section



	in	out	
$\varepsilon_{x,norm,RMS}$	0,10	0,14	mm.mrad
$\varepsilon_{y,norm,RMS}$	0,10	0,16	mm.mrad
$\varepsilon_{z,norm,RMS}$	0,06	0,63	mm.mrad
Energy	0,58	12,42	MeV/u
Transmission		93	%
Beam current		~20	pnA

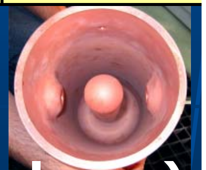
(quadrupole gradients below 20 T/m)

PIAVE-ALPI resonators upgrade and their impact on beam final energy

AGATA demonstrator, RNB accel. project

		2007	2008	Funded	Mid β upgrade	High β extension	
Resonators Upgrade Phases	CR03	0	5	5	5	5	E_{acc} [MV/m]
	CR04-CR06	3,5	3,5	5	5	5	
	CR07-CR20	4,2	4,2	4,2	5,5	5,5	
	CR21-CR25					5,5	
Present ECRIS, stable beam	$^{132}Xe^{20+}$	*7,1*					Energy [MeV/A]
New ECRIS, stable beam	$^{132}Xe^{26+}$		10,3	10,76	12,3	14,3	
Charge breeder, RNB	$^{132}Sn^{20+}$			8,7	9,8	11,3	

Low β_0 res. upgrade, new ECR (funded)



Further mid β_0 cavity upgrade (cheap)

Five additional high β_0 cryostats

Lower β_0 section
Full Nb, 80 MHz, β_0 0,047-0,055

Medium-High β_0 section
Nb/Cu, 160 MHz, β_0 0,11-0,13

Outlook

- Since 20 yrs LNL have been involved in R&D of low beta resonators (QWRs in Pb/Cu, full Nb, Nb/Cu, SRFQs, *cavities for high current applications*)
- ALPI (and then PIAVE), currently working for an intense N.P. experimental programme (70% rejection factor), are steadily improving their perfomance
- The opportunities offered by the AGATA array and the SPES project are giving further momentum in the same direction

Thanks to: A.M. Porcellato, A. Facco, P. Posocco