Particle Therapy

FFAG in PT: an industrial perspective

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BNL, May 18 2006

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Summary

- **The market of particle therapy equipment**
- **Main specifications for proton therapy accelerator**
- **Main specifications for carbon therapy accelerator**
- **Current technologies: the cyclotron**
- **Current technologies: the synchrotron**
- **The FFAG as an alternative**
- **My current issues:**
  - The acceleration cavities
  - The extraction
  - The lower energy gain (number of stages, cost)
- **Conclusions**

1) The market

The market of particle therapy equipment

- Over the last decade, and excluding 2006, 14 proton therapy systems (average 1.4 / year) and one carbon therapy system have been ordered to industry
- Two carbon therapy systems are under construction by national laboratories
- In 2006 only, 4 to 6 proton therapy systems and probably one carbon therapy system will be ordered to industry
- The potential market for future low cost (15 M$), small size PT systems is estimated to be 40 systems/year in the period 2010 - 2020

The price of particle therapy accelerators

- Proton therapy systems are sold for 30 – 55 M$
- Carbon therapy systems are sold for 80 – 130 M$
- The cost of the building, infrastructure, imaging equipment etc. typically doubles this investment
- The accelerator represents generally less than 25% of the price of the system
- A proton therapy cyclotron is sold around 7 M€ (9M$). Cost of goods sold (COGS) is typically 60% of this.
- 400 MeV.U carbon accelerators for therapy are sold for 25 to 40 M€ (32 to 51 M$)

Sales in proton therapy (1995 -2001)

1995	MGH (Boston)	IBA
1996	NCC-Kashiwa	SHI/IBA
1996-1999	Tsukuba University	Hitachi
	Wakasa Wan	Hitachi
	Shizuoka Prefecture	Mitsubishi
2001	PSI (cyclotron only)	Accel
	Wanjie	IBA
	CAI (delayed)	IBA

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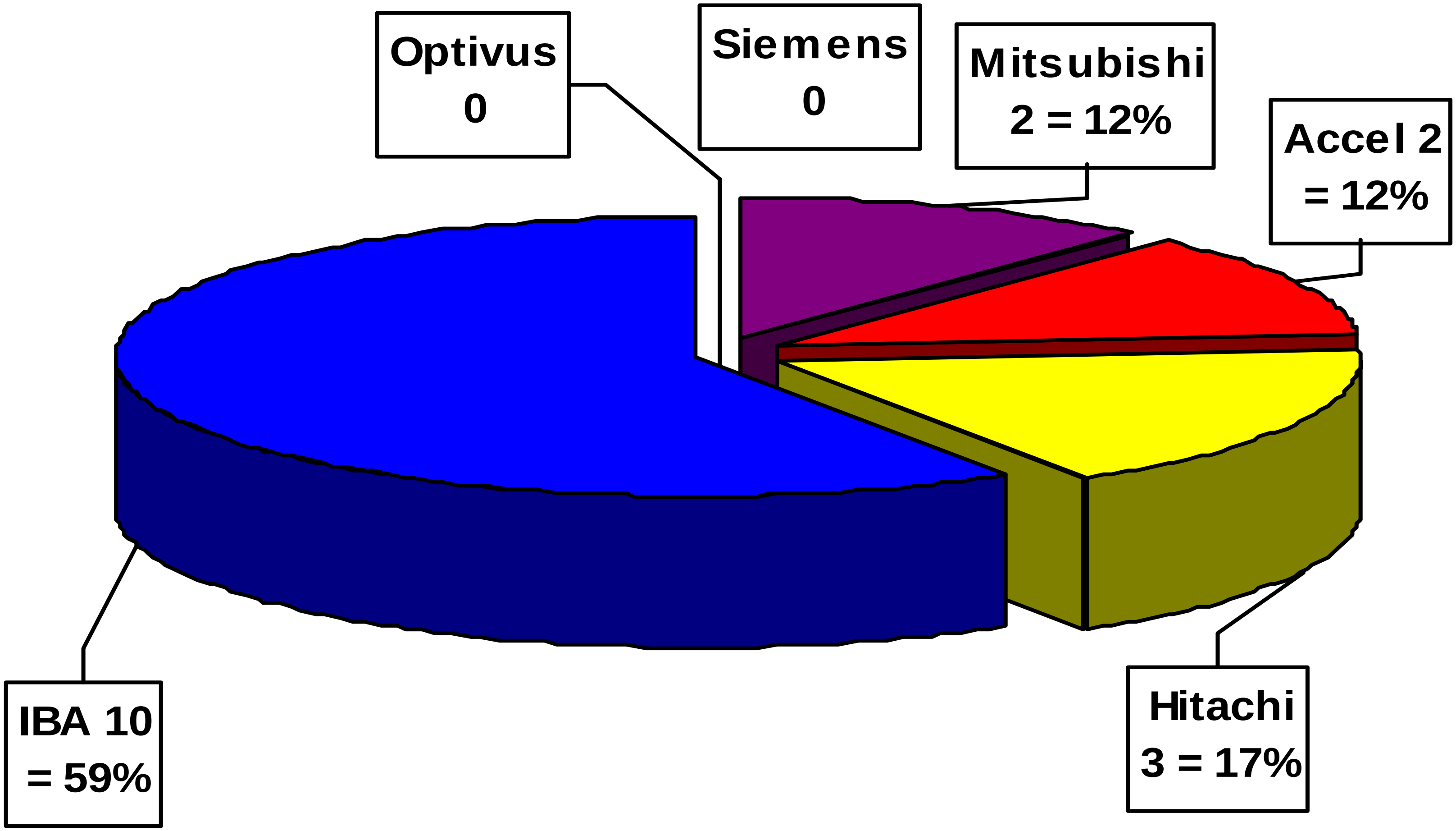
Sales in proton therapy (2001 - 2006)

2002	Rinecker Clinic	Accel
	NCC Korea	IBA
	IUCF/MPRI (gantries only)	IBA
	MDA	Hitachi
2003	University of Florida	IBA
2005	Minamitohoku Hosp.	Mitsub.
2006	University of Essen	IBA (?)
	Hampton university	IBA (?)
	University of Pennsylvania	IBA (?)
	Orsay	???

Market shares in proton therapy



Proton therapy accelerator specifications

Proton therapy accelerator specifications

- Energy variable from 70 to 230 MeV
- Current rapidly and accurately adjustable from 0.2 to 10 nA at treatment head entrance
- Fast energy change (2 sec)
- Fast, accurate current modulation (up to some kHz)
- Safety, Reliability, availability (over 98%), maintainability
- Reasonable power consumption
- Small floor space
- Low cost

Carbon therapy accelerator specifications

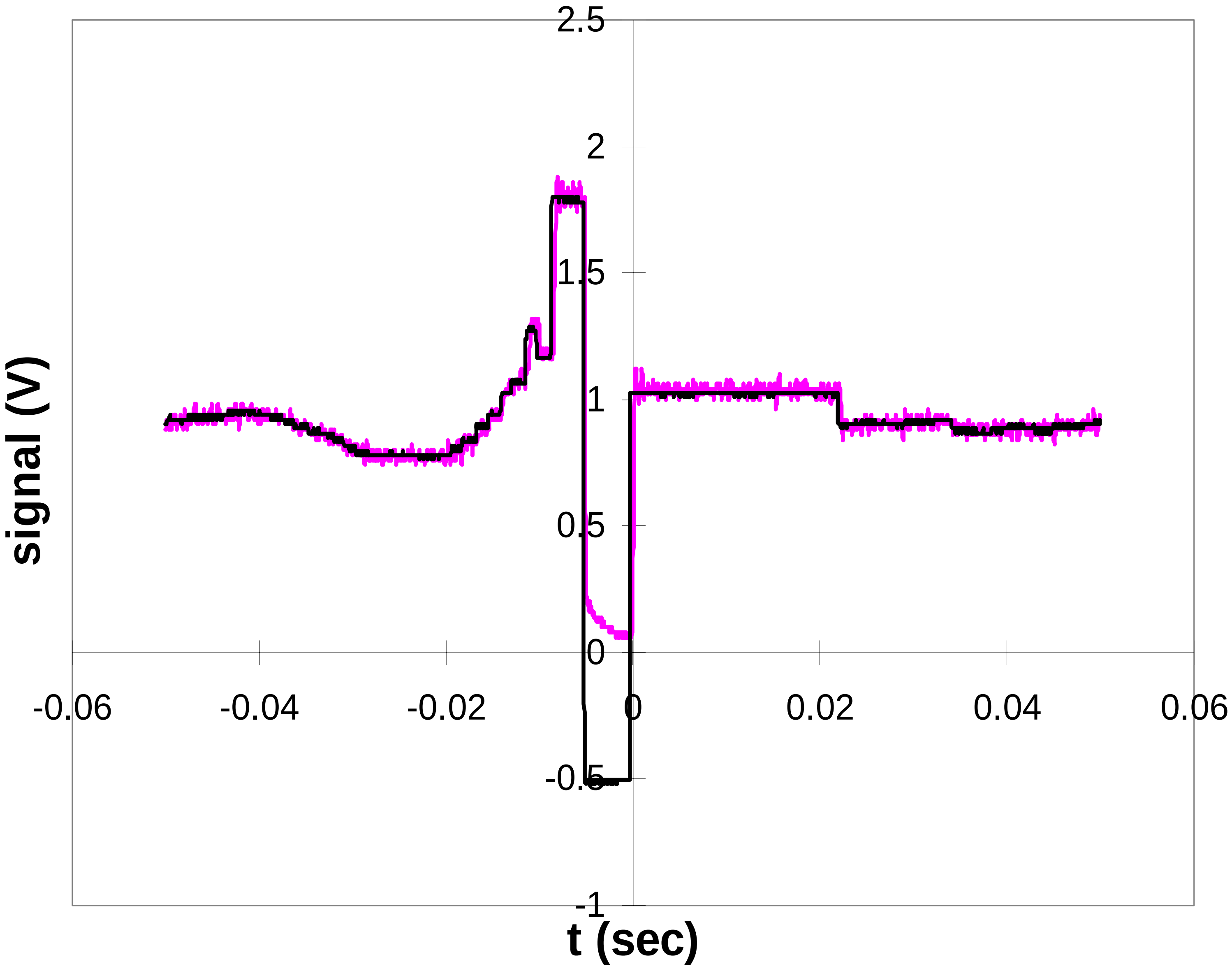
Proton therapy accelerator specifications

- Accelerates protons, alphas, carbon ions (and others if possible)
- Energy variable from 100 to 400 MeV.U
- Current rapidly and accurately adjustable from 0.01 to 0.5 pnA at treatment head entrance
- Higher currents desirable at accelerator exit for secondary beams
- Fast energy change (2 sec)
- Fast, accurate current modulation (up to some kHz)
- Safety, Reliability, availability (over 98%), maintainability
- Reasonable power consumption

Cyclotrons

Cyclotrons for Carbon therapy?

- **In 1991, when IBA entered in PT, the consensus was that the best accelerator for PT was a synchrotron**
- **IBA introduced a very effective cyclotron design, and today the majority of PT centers use the cyclotron technology**
- **Over these 15 years, users came to appreciate the advantages of cyclotrons:**
  - Simplicity
  - Reliability
  - Lower cost and size
  - But, most importantly, the ability to modulate rapidly and accurately the proton beam current


2.5
2
1.5
1
0.5
0
-0.5
-1
-0.06
-0.04
-0.02
0
0.02
0.04
0.06
signal (V)
t (sec)

Why is this important for the user?

- Fast current modulation allows multiple repainting of each layer of the tumor
- Multiple repainting give much higher immunity against organ motion during irradiation
- A faster system is more suited for 4D conformal treatments

The IBA Carbon cyclotron design

- **Superconducting isochronous cyclotron, accelerating Q/M = 1/2 ions to 400 MeV/U (H2 +, Alphas, Li6 3+, B10 5+, C12 6+, N14 7+, 016 8+, Ne20 10+)**
- **Design very similar to IBA PT cyclotron, but with higher magnetic field thanks to superconducting coils, and increased diameter (6.3 m vs. 4.7 m)**
- **Maintains the simplicity and operational advantages of IBA current cyclotron design**

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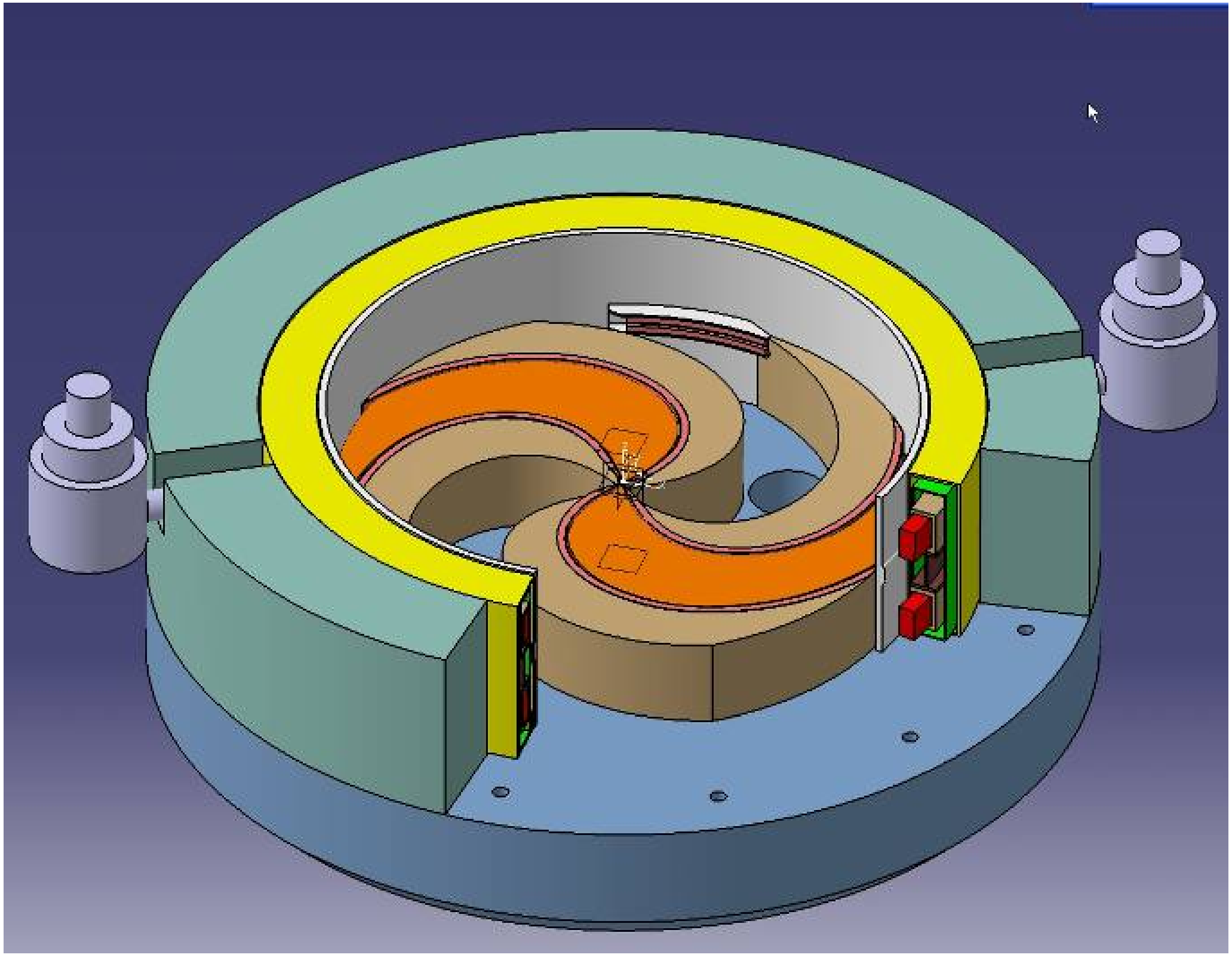
C230 inside view

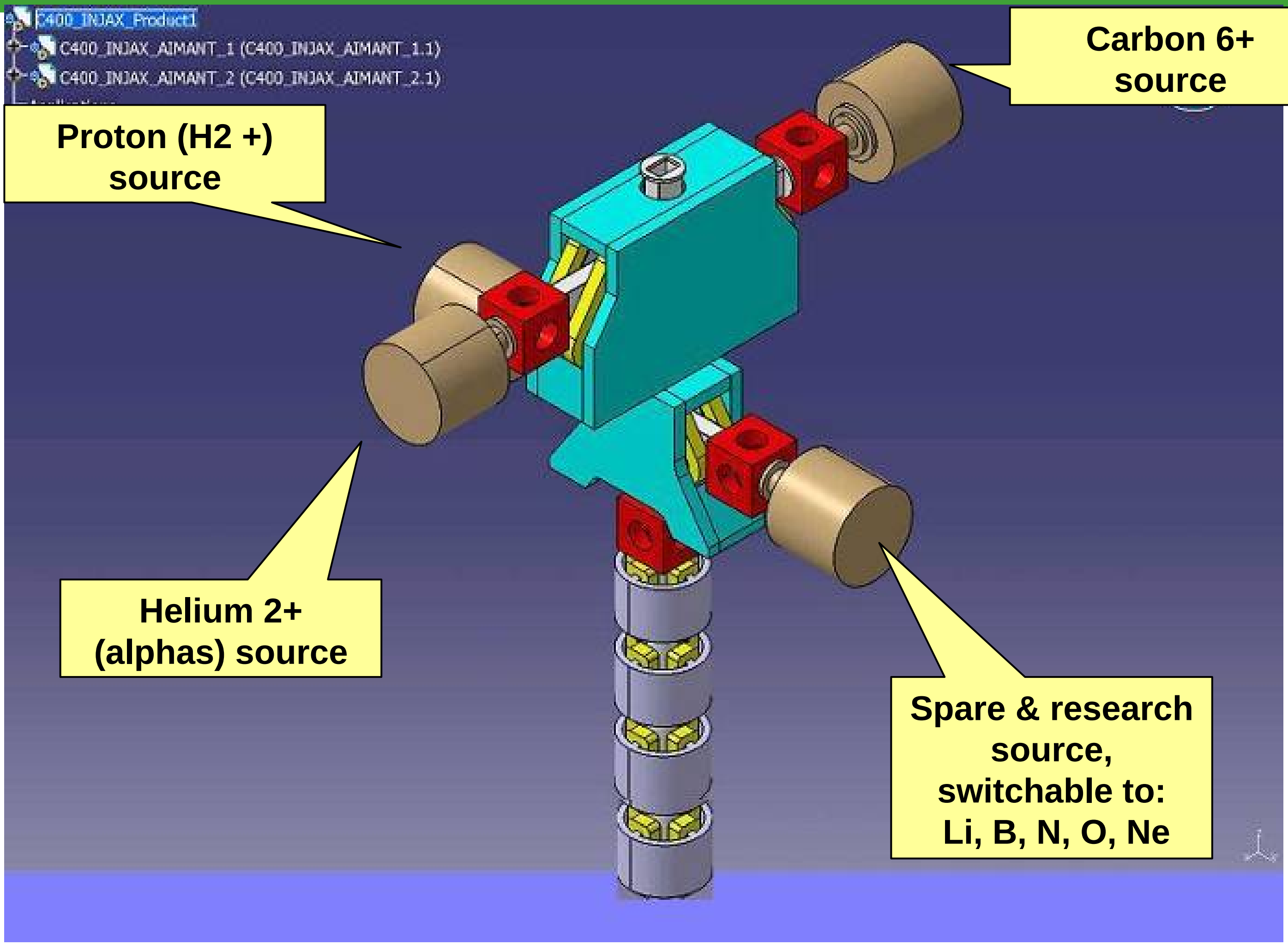
Progress on the design of the carbon cyclotron

- Over the last year, a large team of Russian physicists of Dubna has been working full time on the design and calculations of the new cyclotron
- At this stage, all major uncertainties have been cleared, and IBA is ready to proceed to the detailed design and construction when an order is received
- Main performances in carbon, alphas and proton beam have been confirmed (including the possibility to switch beam in less than one minute)
- A new interesting result is the production of useful beams of C11 in the energy degrader, and good separation in the beam line

Engineering view of the 400 MeV/u cyclotron



Four ion sources allow quick change of ion



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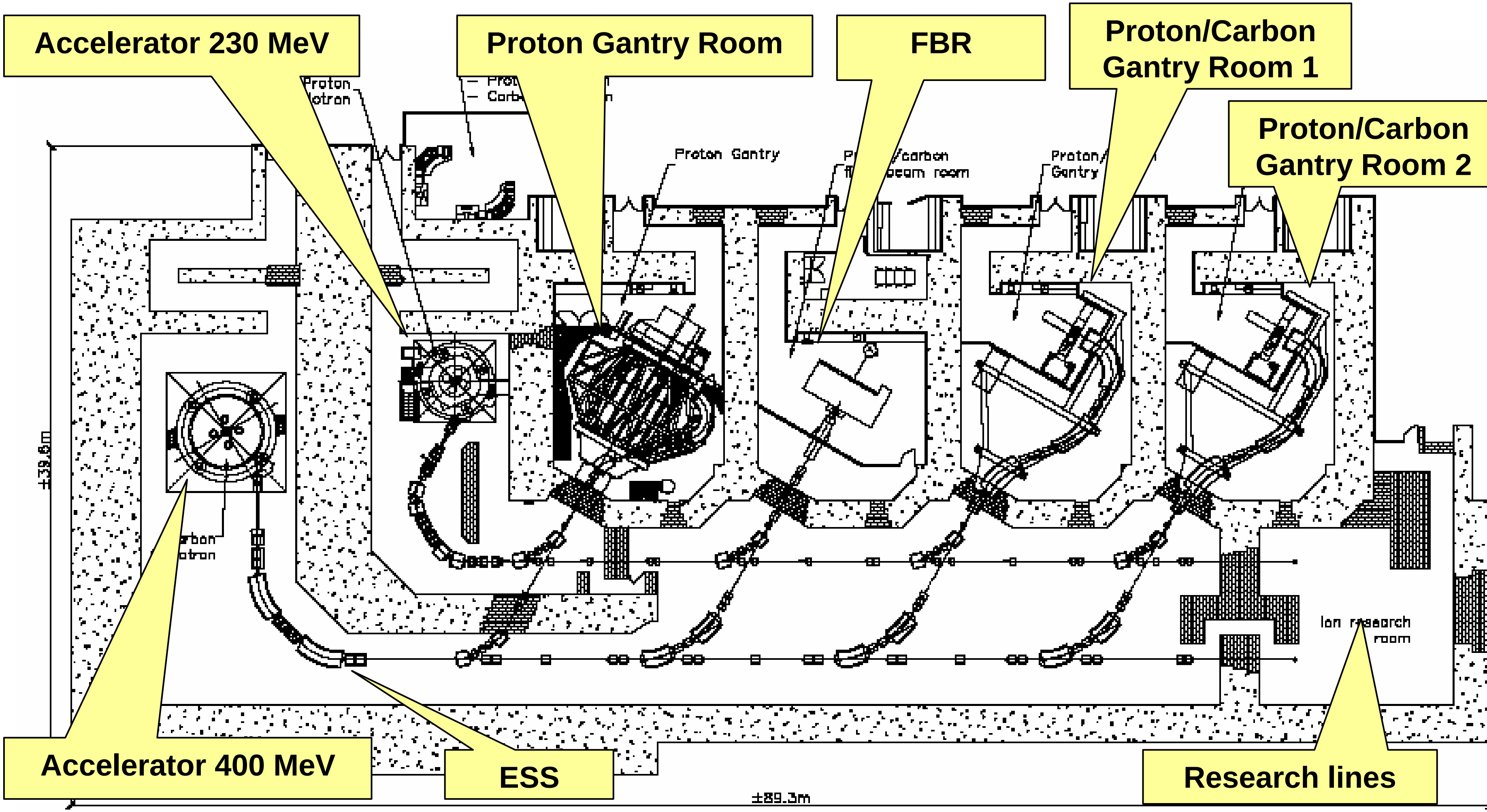
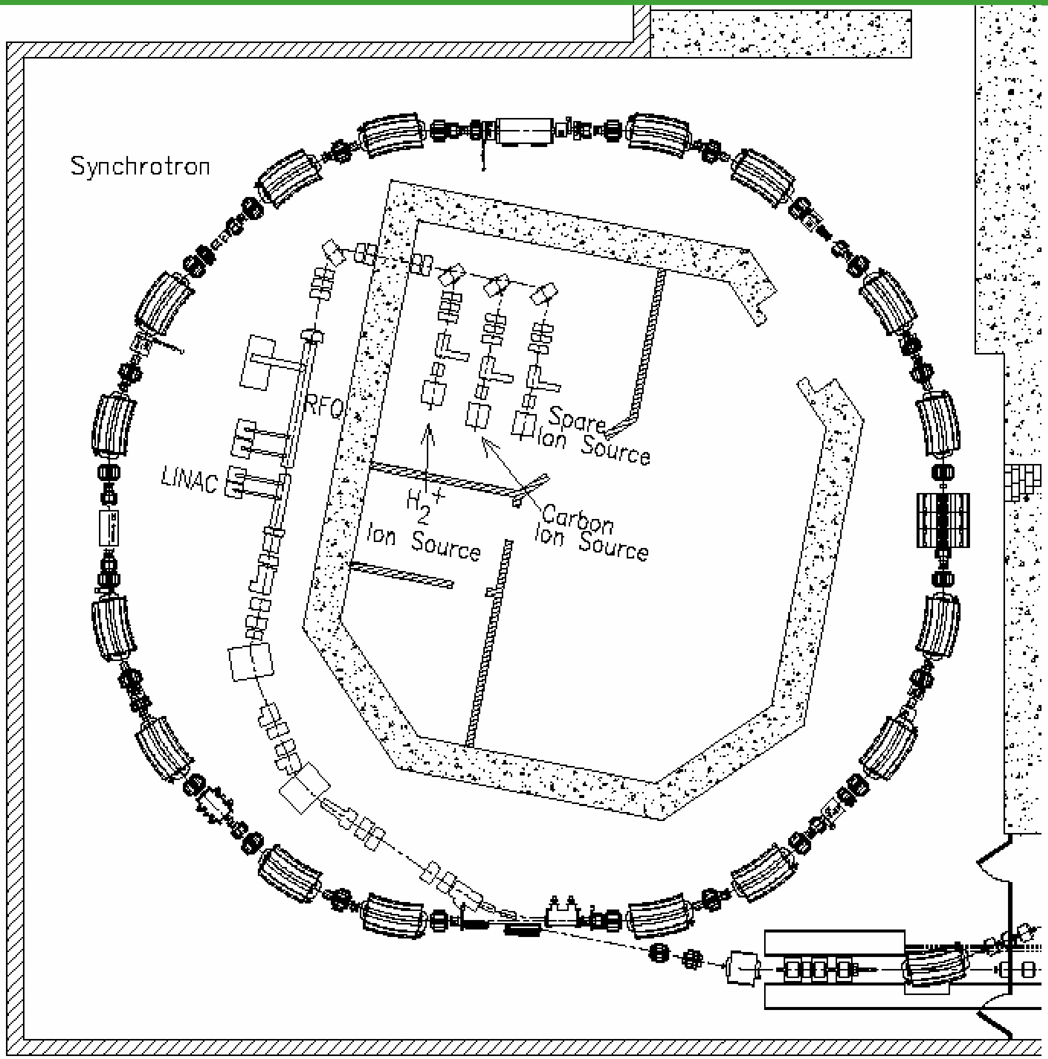
Supernanogan ion source from Pantechnik

The Mayo proton-carbon facility



The PIMMS-CNAO synchrotron for hadron therapy

The proposed PIMMS- CNAO synchrotron



Why the PIMMS design?

- Because it is in our opinion the best synchrotron design available for this purpose.
- Because the PIMMS design has been jointly developed by several European Hadron projects, and is being constructed in Italy (CNAO): a large body of experience will therefore be available on this design.
- The PIMMS design is extremely well documented and the basic design is available free of charge to the industries of the CERN member states
- In addition, IBA is negotiating a license agreement with INFN-CNAO to get a license on the detailed design, production files and beam tuning experience of CNAO

FFAG's in proton and carbon therapy?

(from Rob Edgecock, CCRLC, RAL)

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Scaling FFAG built in Japan

FFAG built or in construction in Japan

	E (MeV)	Ion	Radius (m)	*k*	Rep rate (Hz)	Comments/1st beam
KEK PoP	1	p	0.8-1.1	2.5		2000
KEK – p therapy	150	p	4.5-5.2	7.5		2003
KURRI – ADSR	200	p	4.54-5.12	7.6	1000	100μA
	20	p	1.42-1.71	4.5		
	2.5	p	0.60-0.99	2.5		Spiral
PRISM	20	μ	6.5	5.0		

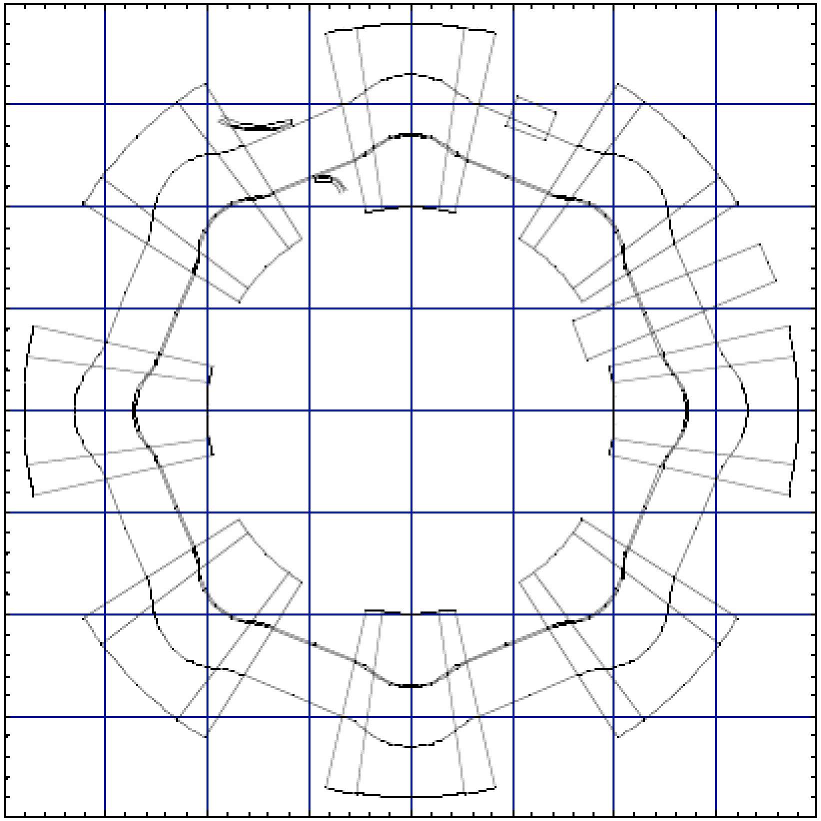
FFAG under study in Japan

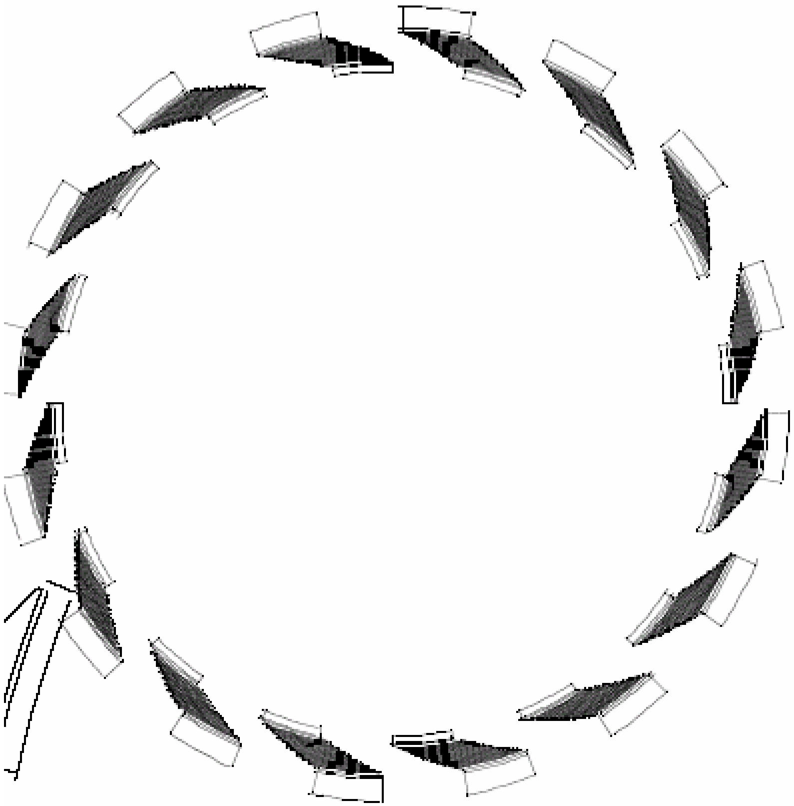
	E (MeV)	Ion	Radius (m)	*k*	Rep rate (Hz)	Comments/1st beam
Ibaraki facility	230	p	2.2-4.1		20	0.1μA, spiral
MEICo - Laptop	1	e	0.02-0.03	0.8	1000	Spiral
MEICo – Ion th.	400	C^{6+}	7.0-7.5	12	0.5	Hybrid, spiral
	7	C^{4+}	1.4-1.8	0.7	0.5	Hybrid
MEICo – p th.	230	p	0.0-0.7		2000	Superconducting, spiral
NIRS Chiba	400	C^{6+}	10.1-10.8	10.5	200	
	100	C^{6+}	5.9-6.7	10.5	200	
	7	C^{4+}	2.1-2.9	6.5	200	
eFFAG	10	e	0.26-1.0		5000	20-100mA, spiral
KURRI BNCT	10	p	1.5-1.6			>20mA
Neutrino Factory	300-1000	μ	20.75-21.25	50	1000	
	1000-3000	μ	79.77-80.23	190	1000	
	3000-10000	μ	89.75-90.25	220	1000	
	10000-20000	μ	199.75-200.25	280	1000	

Advantages of FFAG in PT according to Y. Mori

	Synchrotron	Cyclotron	FFAG
Intensity (>100nA)	Low 1-16nA	Plenty	Plenty >100nA
Maintenance	Normal	Hard	Normal
Extraction eff (>90%)	Good	Poor <70%	Good >95%
Operation	Not easy	Easy	Easy
Ions	Yes	No	Yes
Variable energy	Yes	No	Yes
Multi-extraction	Difficult	No	Yes

Mitsubishi design for Carbon therapy





Particle C^{4+}

Energy 0.035 to 7 MeV/u

Rep. Rate 0.5Hz

1.2×10^{10} ions/s

Particle C^{6+}

Energy 4 to 400 MeV/u

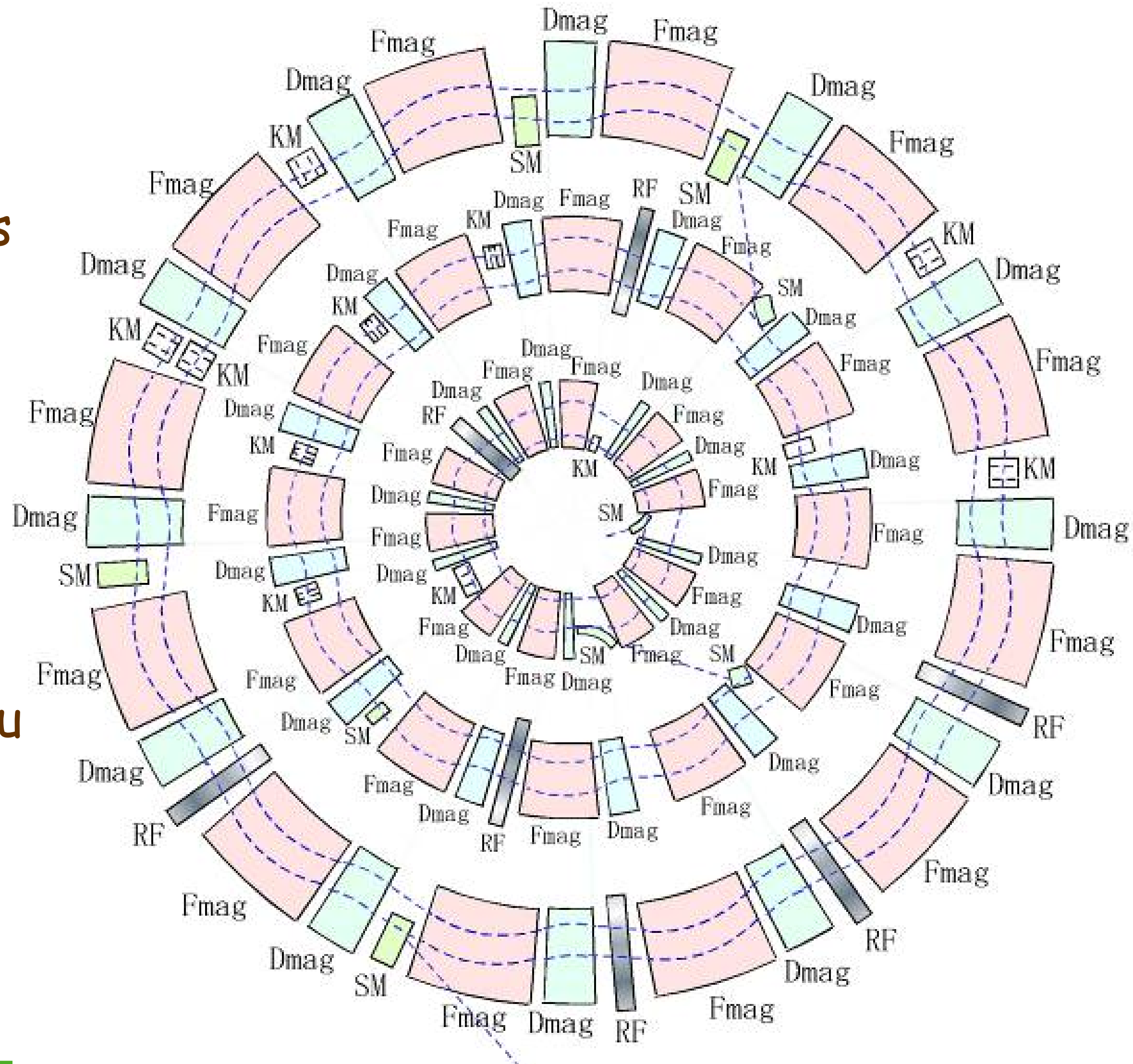
Rep. Rate 0.5Hz

HIMAC design for carbon therapy

LE: C^{4+}
0.04 to 7 MeV/u
2.1 to 2.9m radius
200Hz

ME: C^{6+}
7 to 100 MeV/u
5.9 to 6.7m
200Hz

LE: C^{6+}
100 to 400 MeV/u
10.1 to 10.8m
200Hz



My issues with FFAG

The RF system for high repetition rates ????

- HIMAC Carbon FFAG: 200 Hz, 66 m circumf.
- Fin = 1.94 MHz, Fout = 3.24 MHz
- Acceleration period: 5 msec
- Number of turns: 12,140
- Total voltage gain required (at 45°): 850 MV
- Voltage gain / turn: 70 kV
- Voltage gain / cavity: 17.5 kV
- Reactance of accelerating cavity (80 pF): 613 ohm
- Power/cavity at Q = 1: 250 kW RF/cavity
- Power/cavity at Q = 10: 25 kW RF/cavity, but then cavity tuning is an issue

The extraction issues

- For high repetition rates, a fast quick-off is possible (but the RF looks unfeasible)
- But for low repetition rates, a slow spill seems needed
- I have not read detailed description of such extractions
- I do not see currently the way to achieve fast and accurate current control, as needed for advanced delivery modes
- Apparently the time structure of the extracted beam of a FFAG will be much inferior to the time structure of a cyclotron extracted beam

The number of stages, a cost issue?

- It seems that the energy / velocity gain in one FFAG stage is limited
- For carbon therapy, 3 stages seem needed
- While the costs have not yet been investigated, multiple accelerators tend to be more expensive
- The low weight of steel, compared to a cyclotron of similar energy, has often been mentioned as an advantage of FFAG (and synchrotrons). But the cost of the steel (210 tons, material + machining) for a PT cyclotron is only around 850 k€ (1.1 M$)

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My conclusions

- **I am not an expert of FFAG, so my conclusions are subjective, and may be based on erroneous premises**
- **In my view, the FFAG remains an intriguing alternative accelerator for proton and carbon therapy, but a number of questions remain open:**
  - Fast or slow cycling? If fast, what about RF power?
  - What about extraction, beam current time structure and beam current control
  - How does the FFAG compares in price to a cyclotron or synchrotron of similar energy.

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Thank you!

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